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FUNDAMENTAL TECHNIQUES OF WEIGHT ESTIMATING AND FORECASTING FOR ADVANCED MANNED SPACECRAFT AND SPACE STATIONS

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16. Abstract

A readily applicable fundamental tool for weight estimating and forecasting is presented for use by managers, planners, and engineers during the concept-definition phase of a manned-spacecraft or space-station program.

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FIGURES

Figure | Page

FUNDAMENTAL TECHNIQUES OF WEIGHT ESTIMATING AND FORECASTING FOR ADVANCED MANNED SPACECRAFT AND SPACE STATIONS

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SUMMARY

The development of weight-engineering technology for manned spacecraft began with the advent of Project Mercury. During Project Mercury, weight trends began to assume many of the patterns previously observed for aircraft and unmanned spacecraft. The Gemini and Apollo Programs continued to add similar weight-trend patterns to the growing data bank. In the preparation of this report, the weight data accumulated during the three space programs were used extensively to develop the fundamental relationships and techniques of weight estimating and forecasting. However, future developments were also taken into account by allowing for increasing spacecraft size and advancing technology so that the fundamental weight-estimating and weight-forecasting techniques can be immediately applied to the basic requirements of advanced manned-spacecraft and space-station design.

In this report, the relationship between manned-spacecraft size and weight is shown to be a primary parameter for engineering estimates. After a weight estimate is made, a compatible weight-growth forecast is made. This forecast depends on the primary parameter of program maturity, which is a function of and is obtained from a combination of time-oriented parameters and from the historically reported weight status of previous programs. This technique, which is applicable to all manned spacecraft including space stations, increases perspective, especially during the early concept-definition phase of a program, and provides answers to the design questions of weight and size. This technique has been used for several years at the NASA Manned Spacecraft Center and has resulted in reasonably acceptable estimates and forecasts.

In this complex age when electronic computers are becoming an increasingly necessary part of aerospace-vehicle design and when packaging techniques are rapidly advancing, it is particularly important to retard unwarranted weight growth. Weight engineers and, more important, program managers and planners must be made more aware of the fundamentals of weight technology. This report, although broad in nature, proposes and attempts to demonstrate that the greatest advances in weight technology can be obtained through fundamental observations of past data and through the application of these observations to future projects.

INTRODUCTION

Research is being carried out throughout Government and industry to find a reasonably reliable method of weight estimating and forecasting in the design for all types of advanced aerospace vehicles. The fundamental relationships of manned-spacecraft weight estimating and forecasting are presented in this report. More significant, however, is the presentation of the observations and positions of managers and planners of advanced-design projects at the NASA Manned Spacecraft Center. These managers and planners now think the potential benefits of accurate weight estimating and forecasting are important enough that serious consideration should be given to the development of more exacting techniques.

So far, research has been limited to the fundamentals of weight estimating and forecasting so that a more logical and inclusive methodology can be developed and ultimately established. A gradual increase in the use of electronic computers to meet particular needs is occurring. The degree of electronic-computer usage depends on the amount of detailed data available and on the integration required. Although some useful applications for electronic-computer usage in weight estimating and forecasting have been found, a tendency prevails for the computer user to become lost in the detail of input and print-out. Nonstandard data-reporting techniques and redirected design impacts compound this condition.

SYMBOLS

A_T surface area of the total design-envelope volume V_T

$A_{T,U}$ unpressurized surface area

D_P pressurized diameter

f_s shape factor $V_T^{2/3}/A_T$

H height

N_C number of crewmen

q dynamic pressure

V_T total design-envelope volume

W_B body-structure weight

$W_{B,P}$ pressurized body-structure weight

$W_{B,U}$ unpressurized body-structure weight

W_G gross weight

$W_{G,P}$ pressurized gross weight

$W_{G,U}$ unpressurized gross weight

W_P propellant weight

W_{PL} payload weight

W_{TO} maximum take-off weight

W_{TP} thermal-protection weight

α angle of attack

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter. Principal measurements and calculations in this report are based on the original units.

DEFINITIONS

Body-structure weight: The weight of the basic and secondary load-carrying members, exclusive of the nonstructural panels used for induced environment-protection systems (refs. 1 and 2)

Design-envelope surface area: The surface area of the aerospace-vehicle envelope, usually defined by the body-structure outer mold line or the induced environment-protection outer mold line

Design-envelope volume: The volume within the aerospace-vehicle envelope, usually defined by the body-structure outer mold line

Design freeze: The point in time or maturity during a design phase when aerospace-vehicle hardware becomes committed to the basic operational configuration

Design-limit weights: The nominal weight and the maximum weight to be expected at a particular spacecraft operational condition; should be used to determine analytically or experimentally all weight-dependent performance

Dry weight: The sum of the weights of the first 16 first-generation codes (shown in figs. A-1 to A-6) of references 1 and 2

Gross weight: The sum of the weights of all 27 first-generation codes (figs. A-1 to A-6) of references 1 and 2 for missiles and space vehicles, or the maximum gross weight listed on page 4 of reference 3 for aircraft

Inert weight: The sum of the weights of the first 21 first-generation codes (figs. A-1 to A-6) of references 1 and 2

Shape factor (also called volumetric efficiency): The nondimensional geometric characteristic of an aerospace vehicle or object defined by $V_T^{2/3}/A_T$, where V_T is the total design-envelope volume and A_T is the total design-envelope surface area

Size: The dimensional geometric characteristics of an aerospace vehicle or object, usually defined by design-envelope volume or design-envelope surface area (or both)

Total-structure weight: The sum of the weights for codes 1.0, 2.0, 4.0, and 6.3 (figs. A-1 to A-6) and for air-breathing engine nacelles and pylons in references 1 and 2 for missiles and space vehicles; or the sum of the group weights on page 2 of reference 3 for aircraft

Weight estimate: The formulated status of a weight before it changes progressively to the status of a calculated or an actual weight

Weight forecast: The predicted projection of a weight from the current status of the design

Weight growth: The phenomenon of the generally unexplained difference between the original weight estimate and the final or actual hardware values (refs. 1 and 2)

Weight margin: The margin existing between the design-limit weight and the current weight at any point in a program

Weight prediction: A predicted value which can be used in conjunction with the weight estimate or the weight forecast (or both)

FUNDAMENTALS

The gross or total weight of any aerospace vehicle has little meaning as a single value. This gross weight W_G must be related to a performance parameter through propellant weight W_P and payload weight W_{PL} so that, for a given vehicle gross weight, an efficiency factor $(W_P + W_{PL})/W_G$ can be determined. This type of weight efficiency is shown in figure 1 for various types of aerospace vehicles. To date, manned spacecraft and manned aircraft represent the lowest weight-efficiency values, and launch vehicles represent the highest values. In other words, propellant and

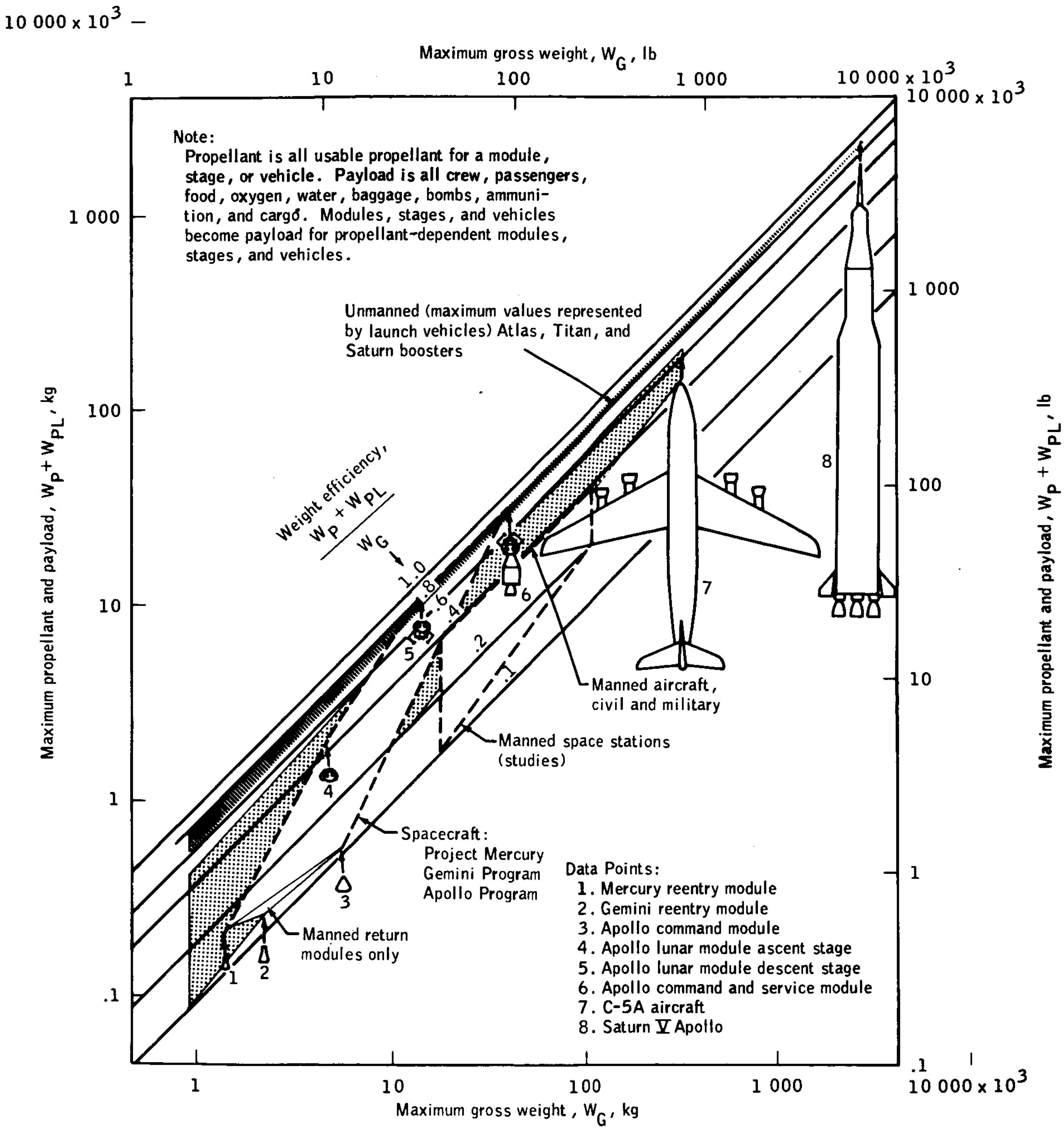


Figure 1.- Weight efficiency of various aerospace vehicles.

payload weights represent a smaller fraction of gross weight in manned spacecraft and manned aircraft than in launch vehicles. The same is true of the relationship of propellant and payload volumes to gross volume.

The density approach to weight estimating and forecasting is used throughout this report and is shown in figure 2. At this point, the design parameter of volume is introduced; thus, the gross weight and the structural weight can be expressed in terms of average density. Several groups of data are identified by type and category of vehicle. Note that body-structure weights of manned spacecraft, fighter-attack aircraft, and bomber and transport aircraft tend to fall within a single band, although a wide range of envelope volumes is covered. Also, the lower shaded band in figure 2 corresponds closely to the body-structure weights of dense unmanned aerospace vehicles. This lower shaded band is also consistent with study data of advanced manned spacecraft and space stations. Therefore, it seems reasonable that the lower shaded band could be used for weight estimates of manned spacecraft and space stations.

The upper shaded band in figure 2 represents the gross weights of manned spacecraft and space stations. This band results from the data for existing manned spacecraft and from many studies of advanced manned spacecraft and space stations. However, most gross-weight-density data of existing vehicles fall above the shaded band. This occurs primarily because the higher bands have a larger propellant fraction of gross weight than manned spacecraft and space stations, which consist primarily of dry weight. Therefore, the upper shaded band seems reasonable for weight estimates of manned spacecraft and space stations.

The fundamental density approach shown in figure 2 provides the principal basis for the estimating and forecasting techniques for manned spacecraft and space stations. It is theoretically possible to predict the weight, density, volume, and shape of a spacecraft from purely theoretical considerations in advance of construction. However, such a calculated prediction would be based on many interrelated assumptions, which may or may not be true, and the calculations would be too complex for practical resolution. In this report, the approach to the relationships between weight, density, volume, and shape is based upon empirical data derived from many aerospace vehicles constructed and flown in the past. The approach is discussed in two phases, estimating and forecasting, where the forecast is the predicted projection of a weight from the current status or an upgrading of any estimate.

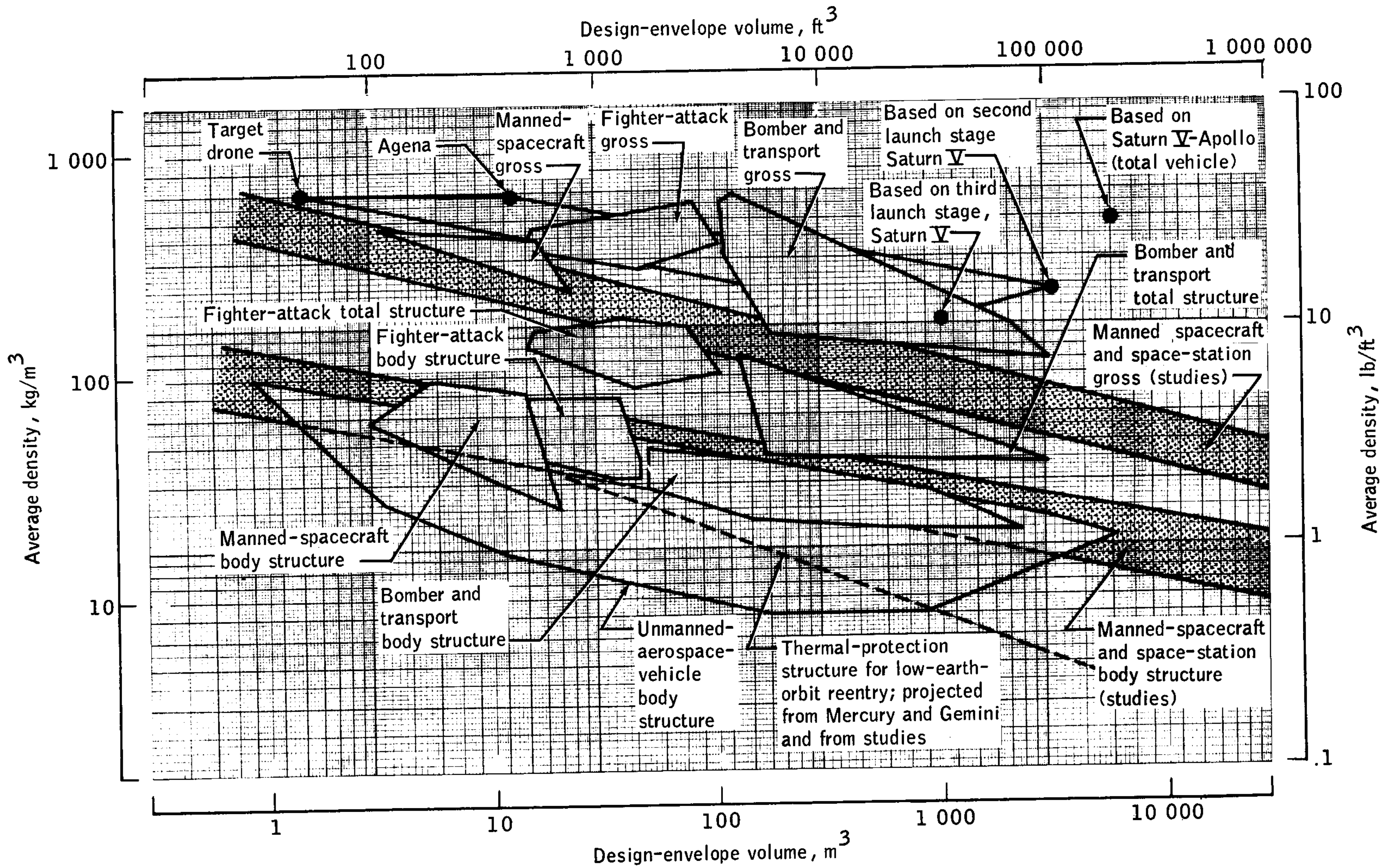


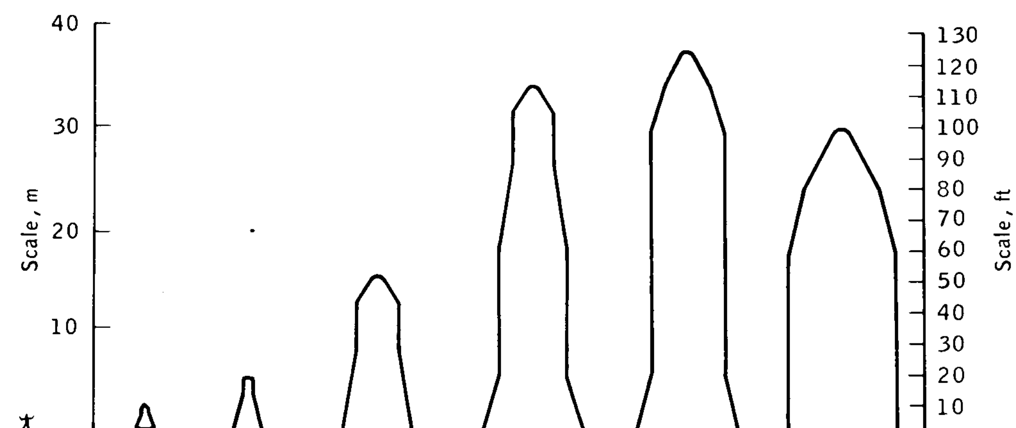
Figure 2. - Relationship between average density and design-envelope volume for aerospace vehicles.

TECHNIQUES

The Estimate

In advanced design, two general approaches to size and weight estimating are used. Either a certain size of a manned spacecraft is desired, and weight is the unknown; or a certain weight is desired, and size is the unknown. These conditions establish the requirements for an integrated size-estimating and weight-estimating technique.

Size. - Size is the parameter that has remained essentially unchanged throughout the design evolution of all manned spacecraft. Although some early-concept sizes did change, the design-freeze sizes did not change by any significant amount during the programs. Size is defined by design-envelope volume V_T. The design-envelope volume generally used is the allowable payload volume of the launch vehicle. This volume is determined principally by the launch characteristics of the launch vehicle, such as maximum $q\alpha$ and bending moments. Examples of launch-envelope geometric data are shown in figure 3.



	Mercury spacecraft	Gemini spacecraft	Apollo spacecraft	Two-stage Saturn V-Apollo spacecraft	Two-stage Saturn V, 75-percent wind condition	Two-stage Saturn V, 75-percent wind condition
Design-envelope volume, m^3	3.11	17.75	254.57	1021.39	1287.00	1906.85
Design-envelope volume, ft^3	110	627	8990	36 070	45 450	67 340
Design-envelope surface area, m^2	12.91	41.62	255.48	724.64	846.35	917.88
Design-envelope surface area, ft^2	139	448	2750	7800	9110	9880

Figure 3. - Spacecraft design-envelope and geometric data.

Throughout the description of the weight-estimating technique, it is important to remember that a manned spacecraft should not necessarily be sized to the allowable payload volume of the launch vehicle. To do this would presume that spacecraft density is not a significant design criterion; as a result, either undersizing or oversizing of the spacecraft becomes a distinct possibility.

Weight. - Density variations of some manned spacecraft are plotted against volume in figure 4. Mercury, Gemini, and Apollo data are relied upon heavily in this plot to establish trend curves A, B, and C. However, other manned-spacecraft studies and large-aircraft-body data are used to determine the slope of curves A, B, and C. Curve A is defined as the apparent minimum density or target density of the vehicle; curve B is the nominal density; and curve C is the maximum density. For example, the weight history of the Mercury spacecraft began at curve A, with the spacecraft undergoing weight growth to a point slightly above curve B. The weight history of the Gemini spacecraft began at curve A, with the spacecraft undergoing weight growth to a point slightly below curve B. The weight history of the Apollo command module began at curve A, with the spacecraft undergoing weight growth to a point slightly above curve C. The variation of these respective weight histories with percent of program completion is illustrated in figure 5.

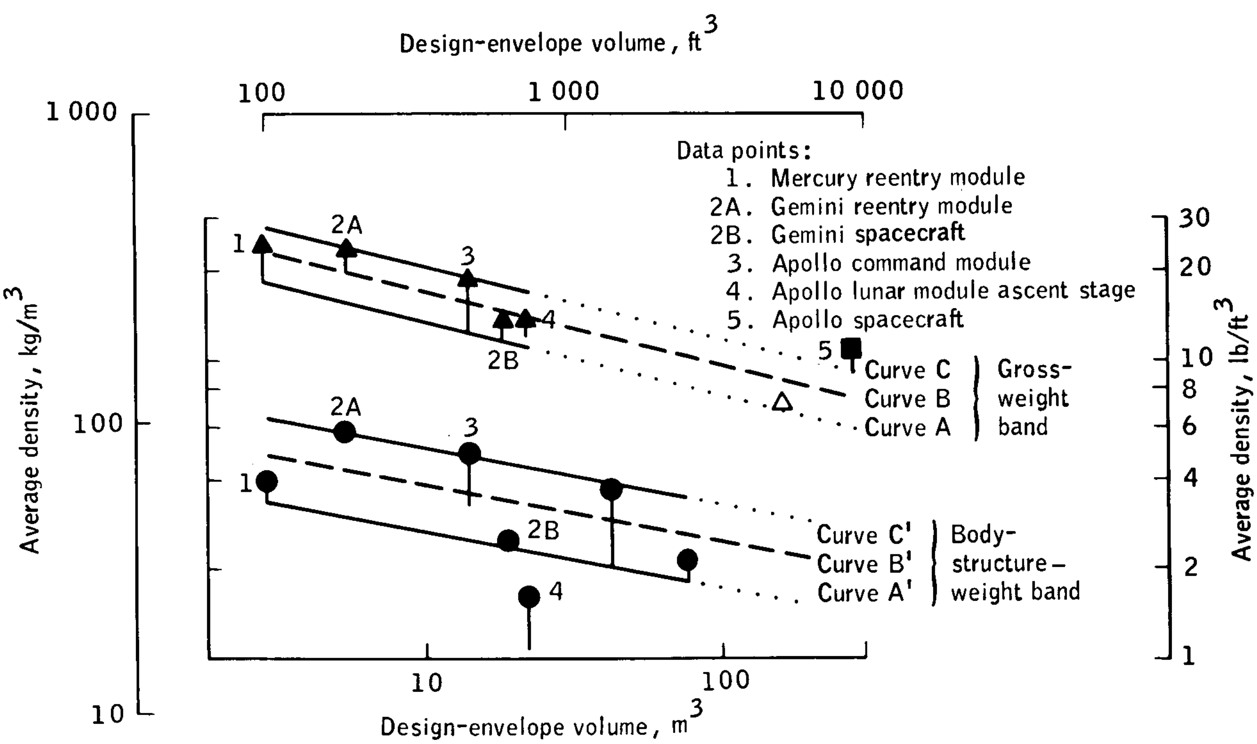


Figure 4. - Spacecraft density-growth history.

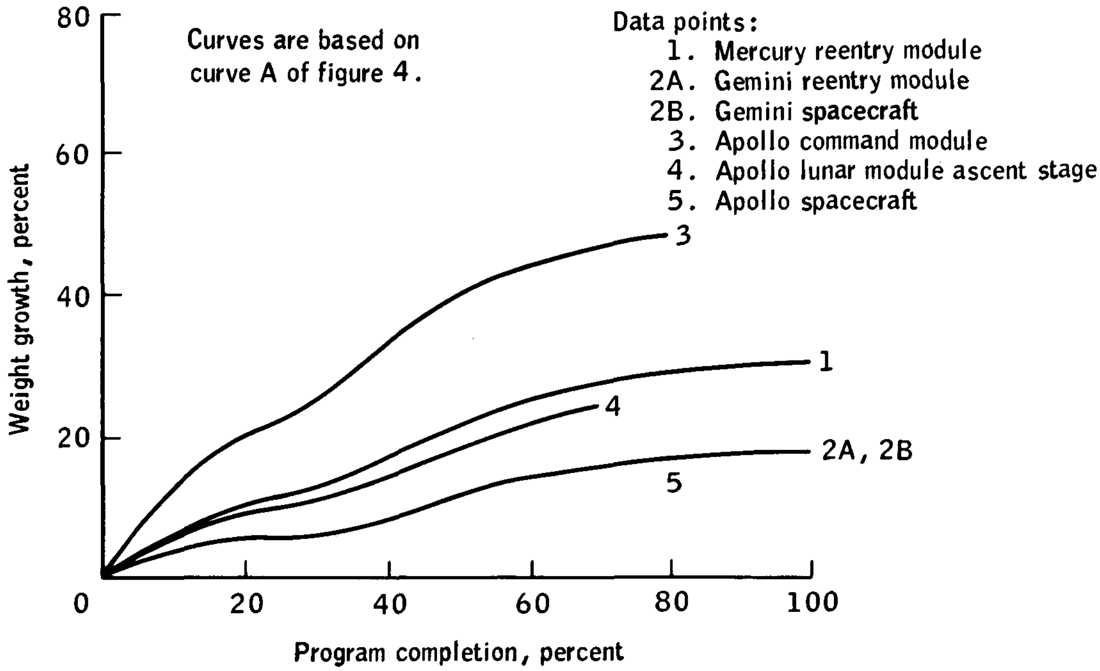


Figure 5. - Spacecraft weight-growth history.

Size and weight. - Information that has been developed from figure 4 to provide first estimates for manned spacecraft is shown in figure 6. Constant gross-weight lines cross the estimating band for various design densities and volumes. Therefore, for any given size, a density and a gross weight are obtained from the selected estimating curve. This generalized estimating technique has the principal advantage of enabling evaluation of the estimate relative to the Mercury, Gemini, and Apollo spacecraft from concept to hardware. Therefore, the various weight estimates that fall either below curve A or above curve C of figures 4 and 6 are subject to additional investigation.

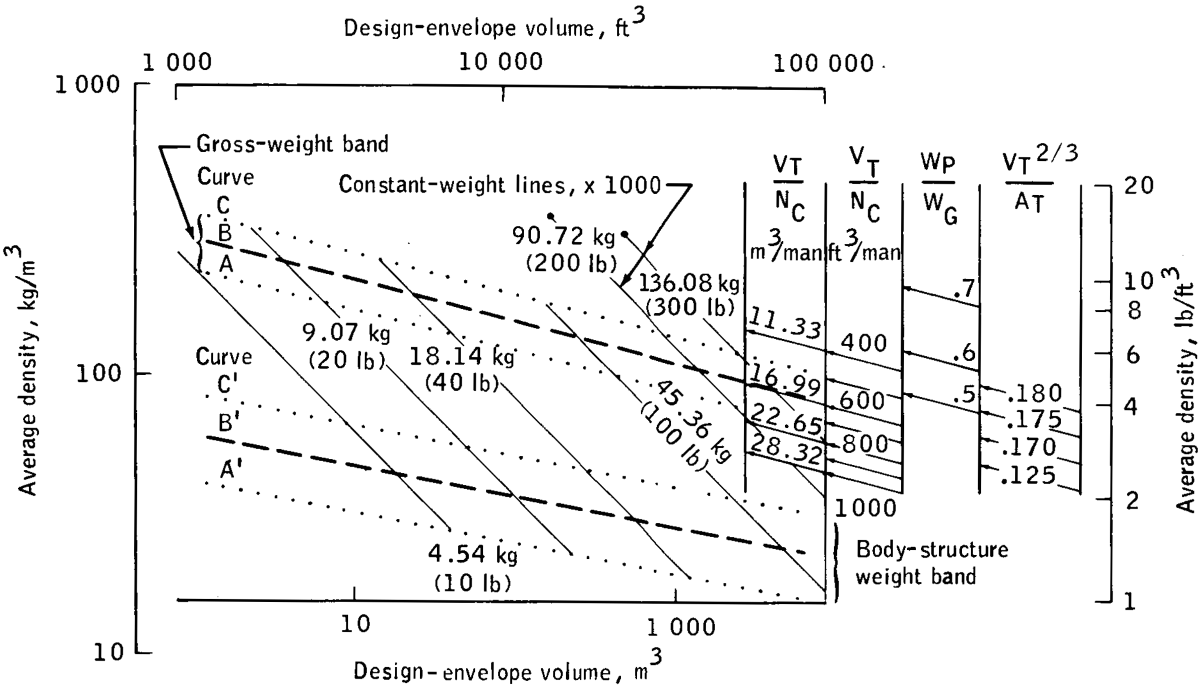


Figure 6. - Weight-estimating technique.

Crew. - The pressurized spacecraft volume per man poses an estimating problem for which no reasonable solution appears to exist, because research data on the volume question vary considerably. An attempt has been made with this technique to use the data that more nearly reflect the minimum volumetric requirements per man, in order to preclude some of the undesirable effects of spacecraft oversizing. To assist in the estimate, a scale of total spacecraft volume per crewmember V_T/N_C, based on data-point information, is shown in figure 6.

Propellant. - The amount of propellant carried in manned spacecraft can vary considerably and is chiefly mission dependent. Therefore, this large variation is accounted for in the estimating technique by the propellant-to-gross-weight relationship for significant data-point information. However, to date, it can be stated only that the estimating band of figure 6 is based on vehicles that have propellant-to-gross-weight ratios as great as 0.5. This value typically is represented by the Apollo lunar module ascent stage. To assist in the estimate, a scale of propellant-to-gross-weight ratio, propellant weight over gross weight (less induced environment protection), based on data-point information, is shown in figure 6.

The important point to be made here is that, unless a conceptual design has a propellant-to-gross-weight ratio greater than 0.5, design densities above curve C (fig. 6) are strongly indicative of a substantially improved capability in packaging technology. The Apollo command module is a case in point. This module, without the heat shield, is less than 10 percent propellant and other expendables by weight, but is twice as dense as the total Apollo spacecraft (fig. 3), which is 60 percent propellant by weight. This variation results from the unusually efficient packaging achieved in the Apollo command module.

Shape factor. - An important spacecraft design parameter that relates directly to the body shape seems to be evolving. The shape factor f_s is defined as $V_T^{2/3}/A_T$, where V_T is the total design-envelope volume and A_T is the total surface area of V_T. This factor has a value of 0.206 for a sphere, a theoretically perfect shape. The value of f_s decreases in relation to the departure of a body from a spherical shape. As a point of reference, most manned-spacecraft bodies have shape-factor values between 0.15 and 0.18, and most aircraft bodies have shape-factor values less than 0.15.

By observing that the spacecraft bodies which have high densities in relation to curves A, B, and C (fig. 4) also have large shape factors and conversely, a shape-factor scale related to the curves of figure 6 can be formulated. This procedure allows, with judgment, an interpolation for estimates between curves A and C of figure 6. This judgment is influenced by such considerations as weight growth and weight margins.

Weight growth. - Weight growth is one of the most undesirable factors in spacecraft design, but weight growth must be considered inevitable throughout the estimating procedure, regardless of the size of the spacecraft. The amount of weight growth that can occur depends on the difference between the estimated density level and the maximum density level for any given design-envelope volume. Weight-growth experience with the Mercury, Gemini, and Apollo spacecraft indicates that a maximum density is definitely approached. The problem of defining the maximum density of a spacecraft, especially an advanced spacecraft, is extremely difficult. Improved packaging technology tends to outdate any attempts to define a maximum-density trend. However, this factor can be kept in mind when estimating spacecraft densities, and it can be related to the latest packaging technology that is available. The advance in packaging technology that occurred from Project Mercury to the Gemini Program and to the Apollo Program is an inherent part of the estimating technique and is one of the principal factors involved in the definition of the width of the estimating band.

Weight margins. - After consideration of size, weight, crew, propellant, shape factor, and weight growth in relation to the weight estimate, the fundamental question of weight margin in relation to the weight estimate remains. Weight margins refer to the program-objective aspects of spacecraft evolution, as distinct from the various design margins, which represent uncertainties such as those relating to stresses, loads, and capacities. The weight margin of a spacecraft is represented by the difference between the spacecraft current-weight estimate and the ultimate performance-weight capability of the launch vehicle. Unfortunately, most design-weight margins are so small that they are used up before the greatest impact on the program by the weight-growth trend.

Because the performance-weight (payload to orbit) capability varies, depending on the launch vehicle and the mission, the question of margins has virtually unlimited answers. The recommended answer is to choose a nominal base-line performance-weight mission for a launch vehicle and begin a sizing, weighting, and weight-margin analysis of the spacecraft from this point of departure. As suggested by figures 5 and 7, a 25- to 50-percent weight margin should be used for advanced designs.

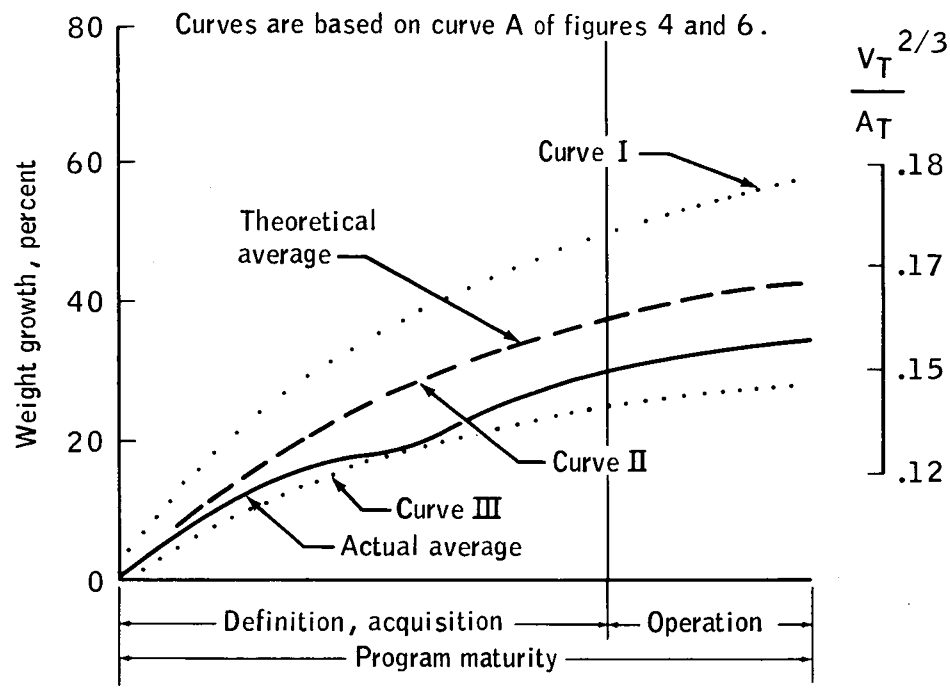


Figure 7. - Weight-forecasting technique.

The Forecast

Weight growth. - In advanced design, the weight philosophy ranges between "the estimates are good — disregard weight growth" to "the estimates are always low — allow for weight growth." The latter philosophy, based on all available data, is emphasized. Therefore, it becomes necessary to develop the forecast to establish the direction and magnitude of the most likely deviation to apply to the estimate. To keep the forecast in the proper perspective with the estimate, the forecast is considered in terms of the significant parameters used for the estimate.

Size, weight, and weight-growth potential. - As has been pointed out, the size and weight of manned spacecraft have a significant relationship that can indicate nominal compatibility. When the relationship between size and weight is not compatible, either undersizing or oversizing for a given weight can result. In addition to the size and weight relationship, weight-growth potential is an important consideration in making a forecast for the estimate. Weight-growth potential must be considered both from the standpoint of the spacecraft independent of the launch vehicle and from the standpoint of the total space vehicle.

If a curve A estimate is made from figure 6, then, in theory, a potential exists for the weight to grow (on the average) as shown by the dashed line in figure 7. However, actual weight-growth curves based on an integrated, reported average assume the S-curve characteristic shown by the solid line in figure 7. The S-curve characteristic is prominent for spacecraft design that must depend on the generally unknown performance of another important portion of the total space vehicle, namely, the launch vehicle and its payload capability. If, during the development of a space program, the launch-vehicle payload capability decreases while the spacecraft weight increases (fig. 8), the natural tendency to maintain positive margins for a given mission forces the two curves toward a more horizontal path. As all of the reported data become more reliable, both curves tend to increase at diminishing rates. This type of integrated history seems to be typical of manned-spacecraft programs and more nearly reflects the actual conditions for each vehicle than a smooth parabolic curve does.

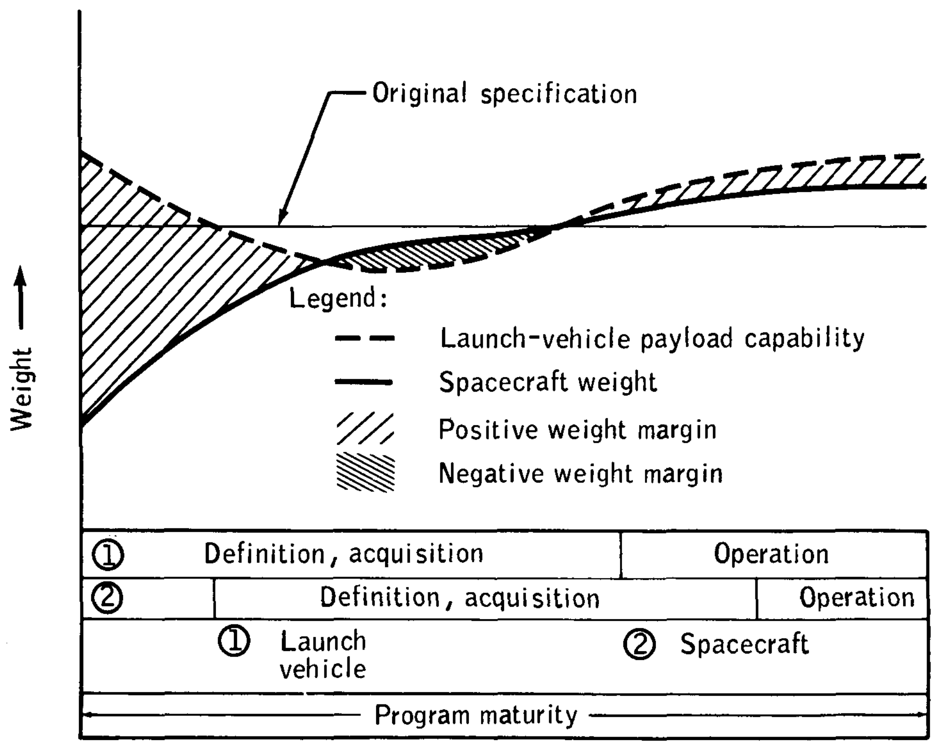


Figure 8. - Typical history of spacecraft weight and launch-vehicle performance.

Shape factor. - As mentioned previously in the discussion of the estimate, the shape factor of a spacecraft body is an important consideration. The shape factor is equally important in relation to the forecast. If a curve A estimate is made from figure 6 and if the shape factor is high (on the order of 0.18), then a theoretical potential exists for the spacecraft weight to grow along curve I of figure 7. For example, the curve A estimate, the shape factor, and the growth curve are typical of the Apollo command module. If a curve A estimate is made from figure 6 and if the shape factor is more nearly an average (approximately 0.17), then, in theory, the weight grows along curve II of figure 7. Also, if a curve A estimate is made from figure 6 and if the shape factor is low (approximately 0.15 or less), a more constrained weight growth, such as curve III of figure 7, theoretically should result. Curve III of figure 7 is also recommended as the minimum weight-growth forecast for any manned-spacecraft program. In other words, forecast curves I, II, and III of figure 7 are based on curve A estimates of figure 6 and on the shape-factor values shown in figures 6 and 7. However, the possibility exists that a design configuration of a manned spacecraft or space station could have a low shape factor (approximately 0.10). In this case, instead of using a curve A estimate (minimum) from figure 6 and a curve III forecast (minimum) from figure 7, it would be advisable to reexamine the design configuration to determine a more compatible weight, size, and shape.

Weight margins. - The weight forecast should be approached in the same sense as margins applied in the estimate and should be related to the program-objective aspects. The idea here is to "think program" while making the forecast. All of this is not to say that some additional margin should not be introduced at this point. In fact, if the design is to have novel features or large advances in the design state of the art, an additional weight margin is recommended. This allowance is especially appropriate when some of the established program weight-estimating procedures within and between agencies and firms have not been sufficiently stabilized by use on several vehicles and several programs.

PROCEDURE

The procedure for weight prediction can be presented best by the use of examples. The following examples demonstrate the flexibility of both the estimate and the forecast.

Example 1 Estimate

Problem. - Estimate the design-limit gross weight, gross-weight potential, body-structure weight, reentry thermal-protection weight, nonstructure-subsystem weight, and payload weight for a manned, low-earth-orbit reentry spacecraft having a volume of 28.32 m^3 (1000 ft^3) and a surface area of 51.10 m^2 (550 ft^2).

Solution. - From the working curves in figure 9, the design-limit gross weight (less reentry thermal-protection weight) is 5897 kilograms (13 000 pounds) (curve B). The body-structure weight (from curve B') is 1429 kilograms (3150 pounds). The reentry thermal-protection weight (from curve D') is 839 kilograms (1850 pounds). The design-limit weight for equipment subsystems and payload, therefore, is 5897 - (1429 + 839) or 3629 kilograms (13 000 - (3150 + 1850) or 8000 pounds).

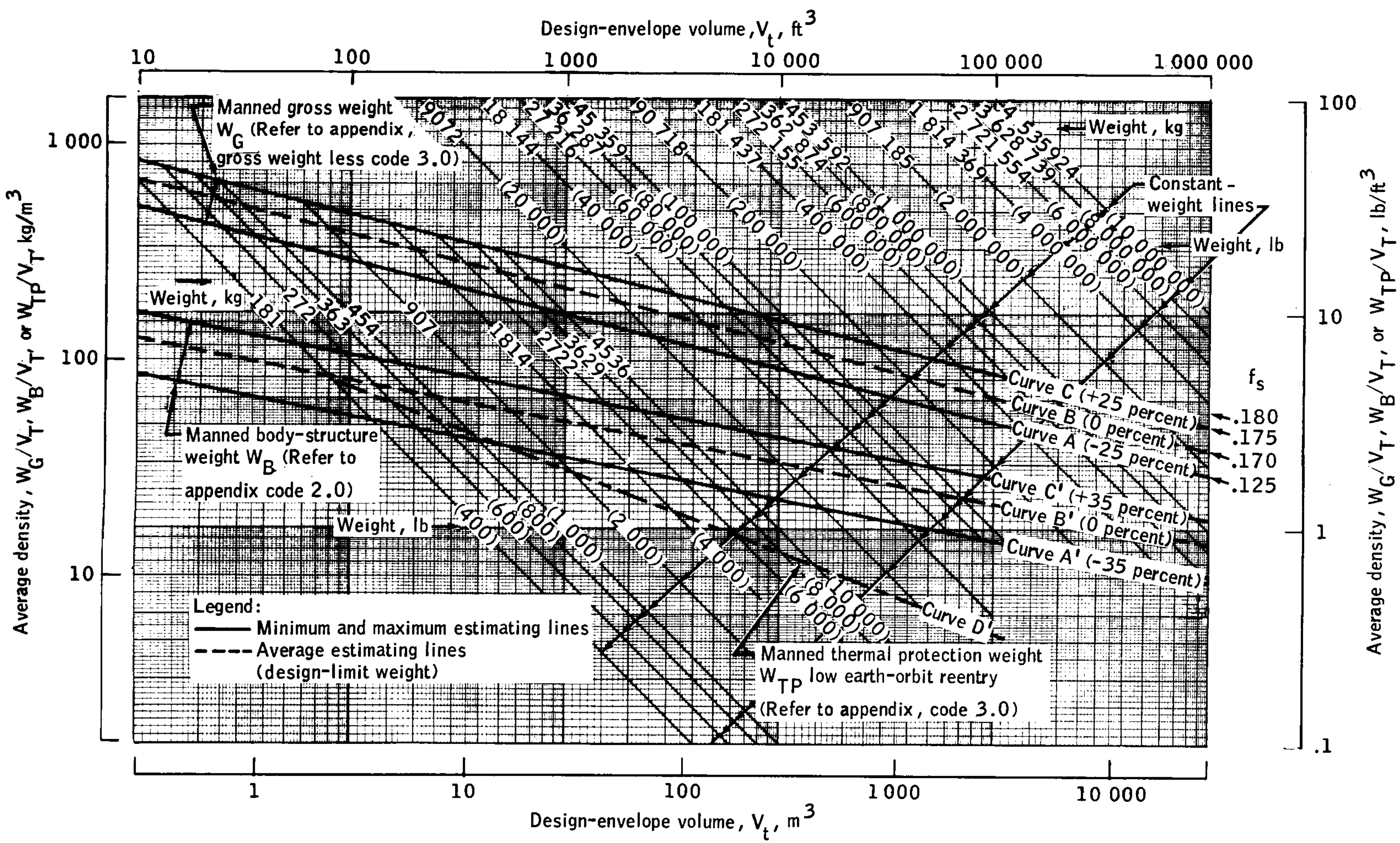


Figure 9. - Manned-spacecraft and space-station weight estimates based on weight, volume, and shape factors.

The f_s is $1000^{2/3}/550 = 0.182$, which indicates potential packaging above curve B. (Curve B of figure 9 represents an f_s of 0.17; a sphere has an f_s of 0.206.) Assume curve C indicates maximum packaging or that the gross-weight potential is 7371 kilograms (16 250 pounds).

Comments. - Because the shape factor is high (approximately the same as that for the Apollo command module), the gross-weight potential should be considered seriously in early design. Micrometeoroid protection is not considered in this example As a general rule, short-term, earth-orbital missions in combination with reentry thermal-protection and body structure preclude consideration of micrometeoroid protection. The design-limit weight for the nonstructure subsystems and payload estimated by figure 9 should be integrated with weight data obtained from additional weight-estimating techniques that rely on mission-oriented parameters.

Example 1 Forecast

Problem.- Apply the design-limit gross weight (less reentry thermal-protection weight) of 5897 kilograms (13 000 pounds) to a complete program span. The W_P/W_G is 0.2, and f_s is 0.182.

Solution. - The design-limit weight of 5897 kilograms (13 000 pounds) could be used to determine weight-dependent performance and cost. This weight is represented by curve B of figure 9. Because spacecraft weight histories range at least between curves A and B of figure 9, curve A appears to be a logical target weight for preliminary contract negotiations. Although this target weight has never been achieved, it should provide an incentive to the contractor to produce a lightweight product. Therefore, figure 10 represents weight growth from the concept-phase weight values to the final hardware weight values at the end of the program. Curve A of figure 9 indicates a spacecraft weight of approximately 25 percent less than 5897 kilograms (13 000 pounds), or 4423 kilograms (9750 pounds). Therefore, this value would tend to follow curve I of figure 10 at a W_P/W_G of 0.2 and an f_s of 0.182. The program-end W_G could be approximately 60 percent greater than 4423 kilograms (9750 pounds), or 7076 kilograms (15 600 pounds). This value closely corresponds to curve C of figure 9, which indicates near-maximum density, based on past manned spacecraft.

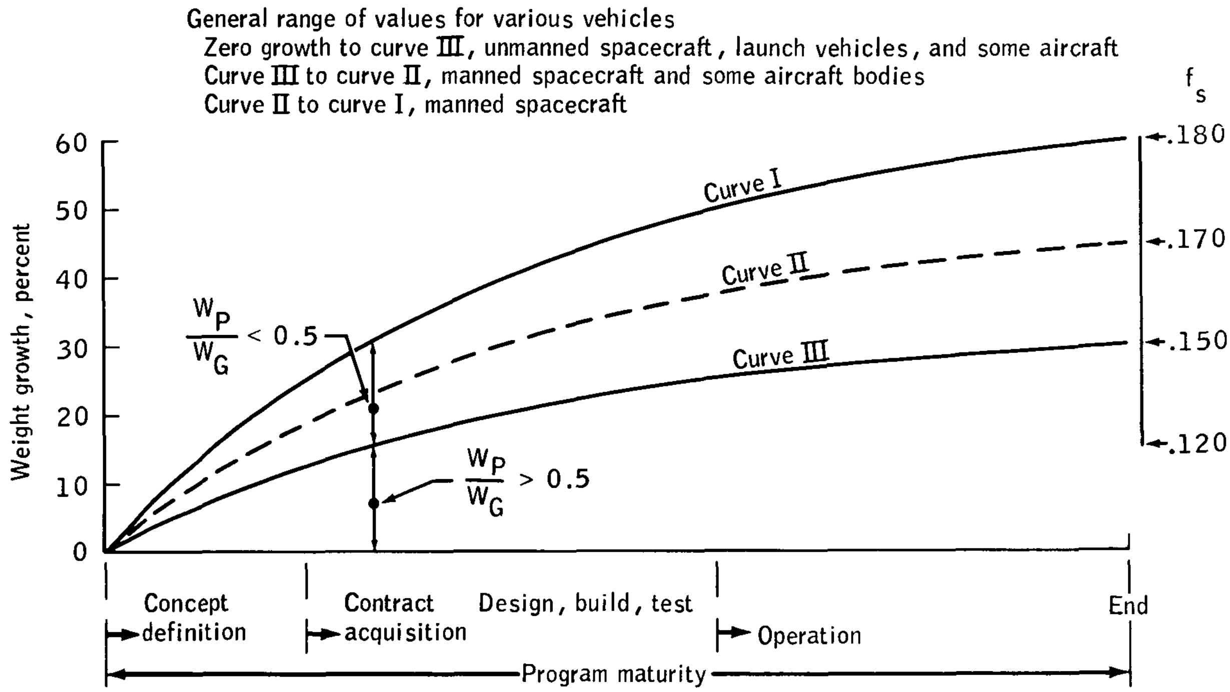


Figure 10. - Weight-growth-forecast curves for first-generation vehicles.

Comments. - The weight values in this example are exclusive of reentry thermal-protection weight, which historically has not experienced significant weight growth. However, secondary impacts of reentry thermal-protection design changes may seriously affect the basic body-structure weight and weight growth. (This effect appears to be most serious when the reentry thermal protection and the basic body structure become integral in function and design.) If the f_s of this example were 0.125 instead of 0.182, based on past information, some doubt would exist about the gross-weight and volume compatibility. Unless the packaging technology improves appreciably and unless the current trend in crew-volume allowances decreases appreciably, an f_s of 0.125 (curve A, fig. 9) indicates no growth potential beyond the target weight of 4423 kilograms (9750 pounds). Therefore, a resizing or reshaping (or both) of the spacecraft would be in order.

Example 2 Estimate

Problem. - Estimate the design-limit envelope volume for a manned space station to be used on an undefined launch vehicle having an estimated base-line payload capability of 45 359 kilograms (100 000 pounds).

Solution. - From the working curves in figure 9, the design-limit envelope volume is determined to be 425 m^3 (15 000 ft^3) for a 45 359-kilogram (100 000 pounds) gross-weight spacecraft (curve B). Various body shape factors can be obtained for various diameters and lengths. In general, shape factors decrease with increasing space-station size because of launch-vehicle restrictions on space-station diameters. Curve C indicates a gross-weight potential of 56 699 kilograms (125 000 pounds). From curve B' of figure 9, the design-limit weight for the body structure is 12 927 kilograms (28 500 pounds). The design-limit weight for nonstructure subsystems and payload is 45 359 - 12 927, or 32 432, kilograms (100 000 - 28 500, or 71 500, pounds).

Comments. - Depending on the surface area, the body-structure weight can be estimated for various diameters. For a 6.71-meter (22 feet) diameter, 424.75-m^3 (15 000 ft^3) cylinder, the surface area is approximately 325.16 m^2 (3500 ft^2), and f_s is 0.175. The f_s in this case coincides with curve C of figure 9 and validates the assumption that the weight of this space station could become as much as 56 699 kilograms (125 000 pounds). Appropriate adjustments to estimated body-structure weight can be made on the basis of surface area and gross weight, as discussed in the section entitled "Example 3 Estimate." Micrometeoroid and radiation protection could be a factor in these estimates, but is not included in this method.

Example 2 Forecast

Problem. - Apply the design-limit gross weight of 45 359 kilograms (100 000 pounds) to a complete program span. The W_P/W_G is 0.4, and f_s is 0.175.

Solution. - The target weight becomes 34 019 kilograms (75 000 pounds) according to curve A of figure 9. The maximum density becomes 56 699 kilograms (125 000 pounds) according to curve C of figure 7. From a target weight of 34 019 kilograms (75 000 pounds), the spacecraft-weight growth would tend to follow curve I of figure 10. With an f_s of 0.175, packaging constraints could occur before the program end, and the spacecraft-weight growth would be inclined toward curve II of figure 10. Because the W_P/W_G is 0.4 in this example, W_P/W_G may be overemphasized in the design-packaging density. For manned spacecraft with a W_P/W_G up to 0.5 (e.g., the Apollo lunar module ascent stage), it is evident thus far that f_s is an important weight-growth indicator, based on the original estimate and the apparent maximum density.

Comments. - The uncertainties of the estimates (in this technique, at least ±25 percent on gross weight and ±35 percent on body-structure weight) suggest that an average design condition may be assumed if curve B and B' values are used from figure 9. For example, both the single-module and the multiple-module design concepts are implied by the backup research data. Specific interpolations for this basic design difference cannot be made realistically in view of the weight growths that have occurred and that range across the entire bands of unit estimates for various given volumes. However, this is not to say that more specific interpolation of estimates should not or could not be done. Studies are currently underway more specifically to assign early estimates to a programmatically related "minimum allowance" as prescribed by basic design criteria for concept configurations.

Example 3 Estimate

Problem. - For the small-space-station configuration shown in figure 11, determine the body-structure weight trade-off data for the given concept, based on conditions A and B shown in the figure. Select a pressurized volume, based on the pressurized diameter.

Mission requirements	Condition A	Condition B
Envelope volume, m^3 (ft^3)	124.59 (4 400)	124.59 (4 400)
Envelope area, m^2 (ft^2)	142.14 (1 530)	142.14 (1 530)
Nose-cone weight, kg (lb)	454 (1 000)	----
Reentry-module weight, kg (lb)	----	6 124 (13 500)
Launch-vehicle maximum payload weight, kg (lb)	18 144 (40 000)	18 144 (40 000)
Space-station design-limit gross weight, kg (lb)	17 690 (39 000)	12 020 (26 500)
Auxiliary-module weight, kg (lb)	4 536 (10 000)	4 536 (10 000)

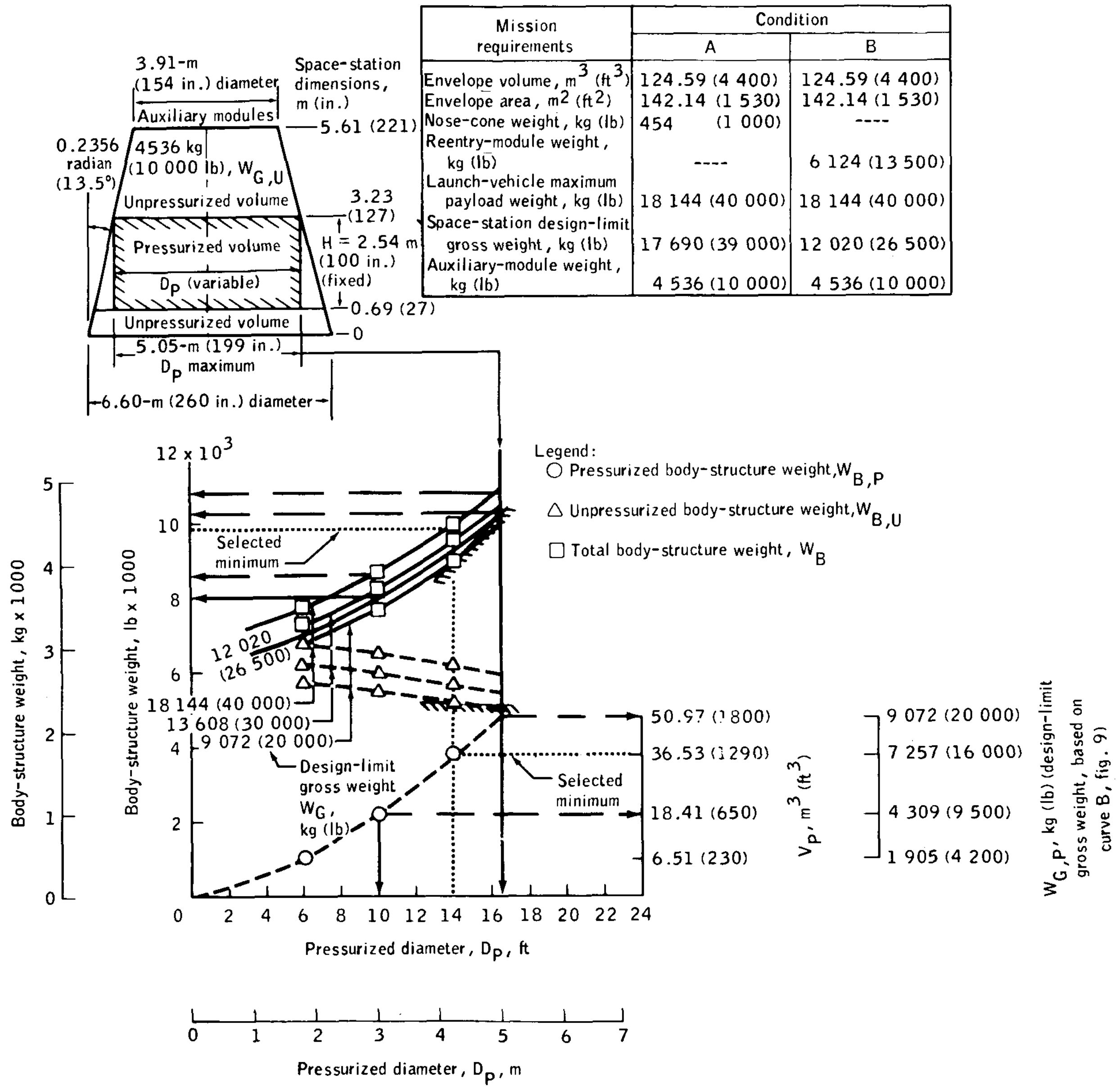


Figure 11. - Body-structure weight and sizing analysis for a conceptual design of a small space station.

The pressurized diameter D_P is variable, and the height H is fixed at 2.54 meters (100 inches). Also fixed is the unpressurized gross weight $W_{G,U}$, 4536 kilograms (10 000 pounds), which is assumed to be the weight of the unpressurized auxiliary modules. The resulting body-structure weights, pressurized, unpressurized, and total body, are plotted against pressurized diameter (fig. 11).

Solution. - The total space-station volume of 124.59 m^3 (4400 ft^3) corresponds to a 18 144-kilogram (40 000 pounds) design-limit W_G (fig. 9). This nominal weight is also the launch-vehicle payload capability. Also from figure 9, the first approximation for the body-structure weight is 4695 kilograms (10 350 pounds).

Assume various diameters for the pressurized volume to determine areas, volumes, and weights; plot the data. For a 3.05-meter (10 feet) D_P, the surface area is 39.02 m^2 (420 ft^2), and the volume is 18.41 m^3 (650 ft^3). From figure 9, 18.41 m^3 (650 ft^3) corresponds to a design-limit gross weight $W_{G,P}$ of 4309 kilograms (9500 pounds). From figure 12, 39.02 m^2 (420 ft^2) and 4309 kilograms (9500 pounds) correspond to a body-structure weight of approximately 998 kilograms (2200 pounds). Approximately 998 kilograms (2200 pounds) is also obtained from figure 9 for 18.41 m^3 (650 ft^3); however, figure 12 is recommended as a cross-check and as a source of additional parameter accountability. The same procedure is followed for a D_P of 1.83 meters (6 feet) and a D_P of 4.27 meters (14 feet), and the resulting data are plotted in figure 11.

The unpressurized surface area $A_{T,U}$, including the two ends, is constant at 142.14 m^2 (1530 ft^2). However, the design-limit gross weight of the unpressurized volume varies, depending on pressurized gross weight $W_{G,P}$. Curve B of figure 12 is used as a base-line shell weight; 2359 kilograms at 142.14 m^2 (5200 pounds at 1530 ft^2) and 5 percent of nonstructure weight are added for structural mounts and supports. (For the manned volume, the comparable factor is approximately 10 percent, which is included in figure 12 estimates.) A plot is made in figure 11 of the unpressurized body-structure weights corresponding to design-limit gross weights of 9072, 13 608, and 18 144 kilograms (20 000, 30 000, and 40 000 pounds). A maximum cylinder gross weight can be extrapolated to approximately 9072 kilograms (20 000 pounds).

Based on fulfilling the mission requirements of conditions A and B, select the pressurized diameter. The total body-structure weight is plotted by adding the values for pressurized and unpressurized body-structure weight in figure 11. It is noted that the values are parallel for 9072, 13 608, and 18 144 kilograms (20 000, 30 000, and 40 000 pounds), except where the base-line shell penalizes the unpressurized and total body-structure weight between 9072 and 13 608 kilograms (20 000 and 30 000 pounds).

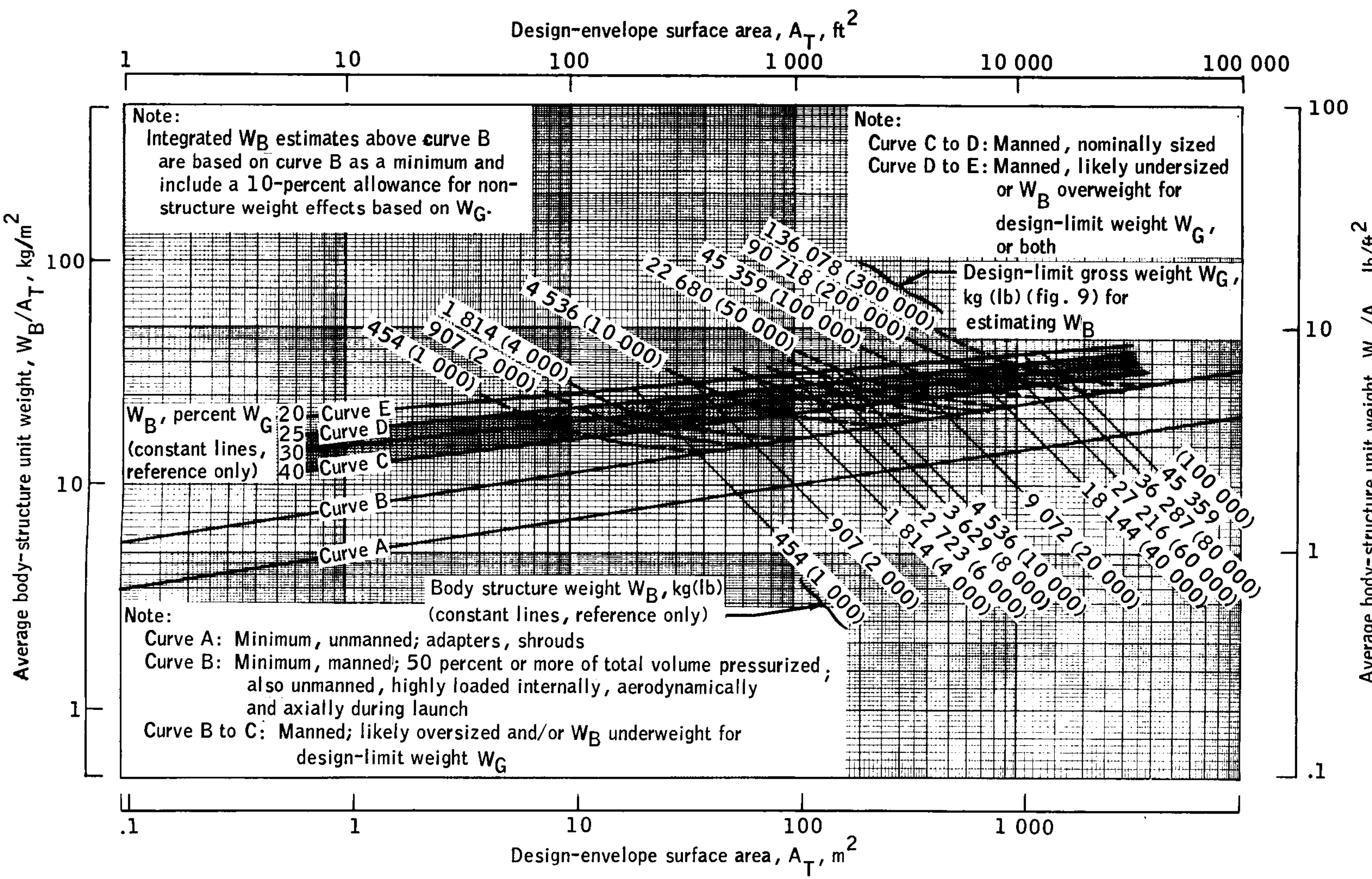


Figure 12. - Body-structure weight estimates based on surface area and gross weight.

If conditions A and B are applied to a D_P of 3.05 meters (10 feet), the resulting total body-structure weight varies between 3629 and 3901 kilograms (8000 and 8600 pounds), depending on the design-limit weight that is chosen, 12 020 or 17 690 kilograms (26 500 or 39 000 pounds). The size of the pressurized module is based on the estimate of 12 020 kilograms (26 500 pounds) to accommodate conditions A and B. When 4536 kilograms (10 000 pounds) for $W_{G,U}$ is deducted, 7484 kilograms (16 500 pounds) remains for $W_{G,P}$. This result indicates a D_P of 4.27 meters (14 feet) closely corresponding to a $W_{G,P}$ of 7484 kilograms (16 500 pounds). The maximum cylinder D_P indicates a $W_{G,P}$ of 9072 kilograms (20 000 pounds) and leaves only 2948 kilograms (6500 pounds) for the $W_{G,U}$ on the basis of a limit of 12 020 kilograms (26 500 pounds). This result indicates an oversized D_P. Therefore, in view of the 17 690-kilogram (39 000 pounds) design condition and weight growth, 4.27 meters (14 feet) is selected as the minimum D_P. The total body-structure weight is 4468 kilograms (9850 pounds) at a design-limit weight of 17 690 kilograms (39 000 pounds).

Comments. - In this example, the approach to body-structure weight estimating involves volume and area as the primary parameters (figs. 9 and 12). This approach provides a cross-check that is desirable, especially when the values obtained by the two parameters are equal or very nearly equal. It is anticipated that, as f_s becomes smaller for any given space-station volume, area becomes an increasingly more important estimating parameter than volume. To date, sufficient analysis has not been made to determine where this crossover point may be in terms of estimating accuracy. It is thought that considerable insight into the volume and area relationship should be provided by aircraft data which reflect f_s values as low as 0.04. If the volume and area relationship or f_s is considered in relation to figure 2, for example, the lowest body-structure weight densities are represented by unmanned aerospace vehicles having f_s values of approximately 0.18 to 0.12. The next highest body-structure weight densities are represented by manned-spacecraft, fighter-attack, and transport and bomber bodies also having f_s values ranging between 0.18 and 0.12. The highest total-structure weight densities are represented by manned fighter-attack aircraft and by transports and bombers having f_s values ranging from approximately 0.04 to 0.08.

Example 3 Forecast

Problem. - Examine weight growth in relation to the selected minimum D_P.

Solution. - A cylinder 4.27 meters (14 feet) in diameter by 2.54 meters (100 inches) high has an f_s of $1290^{2/3}/675 = 0.177$. From figure 9, this f_s indicates gross-weight potential above curve B and possible weight growth above the chosen nominal design-limit gross weight. A gross weight of approximately 10 433 kilograms (23 000 pounds) at an f_s of 0.177 and a volume of 36.53 m^3 (1290 ft^3) is indicated by figure 9. If the maximum cylinder diameter is chosen so as to account for gross-weight potential, it should be remembered that the corresponding f_s would be 0.171, indicating a possible packaging constraint near 10 433 kilograms (23 000 pounds). Also, the 4536-kilogram (10 000 pounds) unpressurized-weight allowance becomes correspondingly less. The minimum allowance in this exercise is 2359 kilograms (5200 pounds), which is based on the minimum base-line shell of the unpressurized surface area.

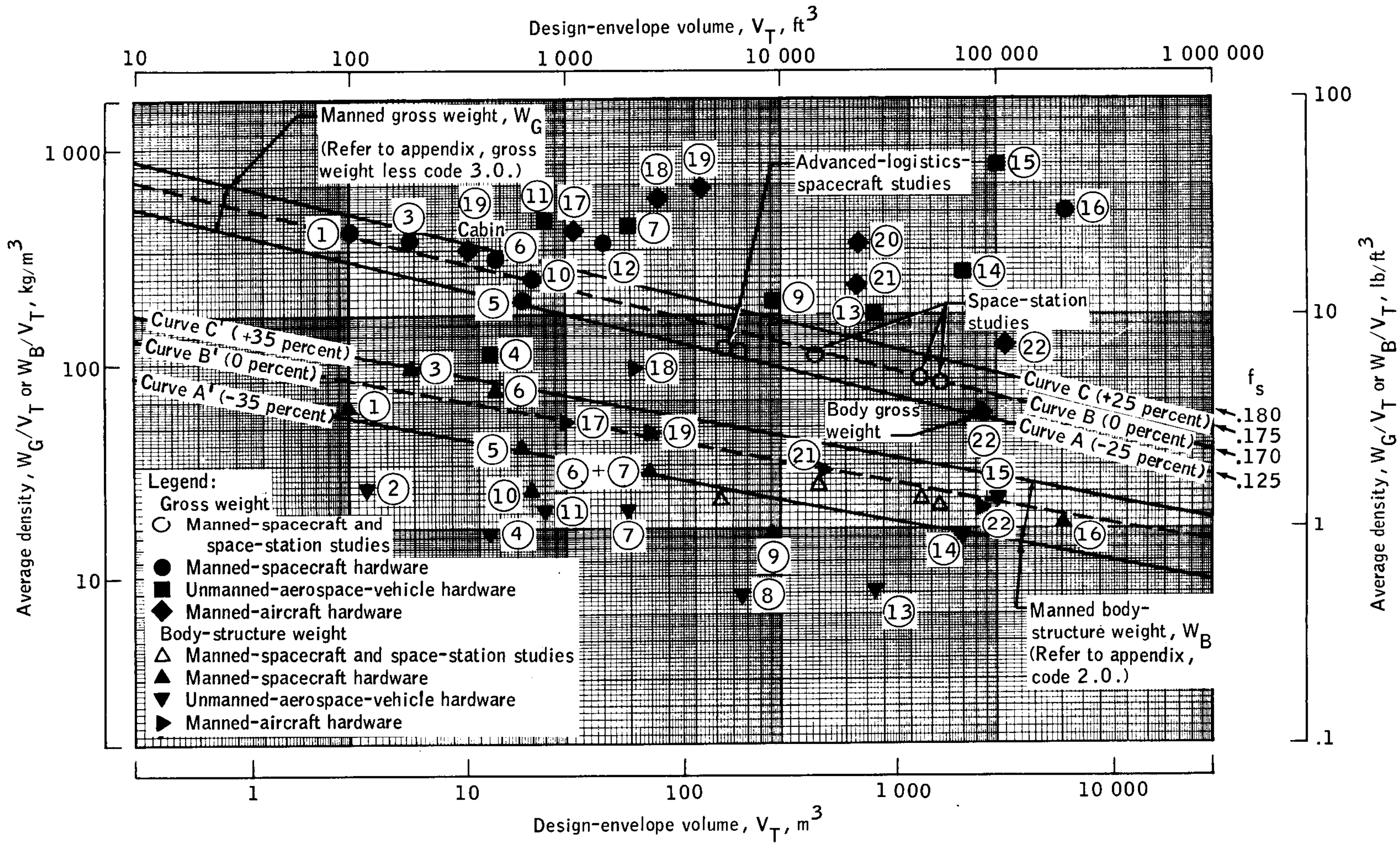
Comments. - It is interesting to note that gross-weight potential or weight growth from nominal values may be approached from two basic and opposing views in conceptual design. The more common view is to assume that the gross-weight potential can be reserved for useful payload (experiments, etc.) and to reflect this view in conceptual weight projections. The other extreme view (and least likely approach) is to assume that the useful payload weight allowance will not increase or may even decrease. Based on experience, it appears that, at best, the useful payload weight may be assumed to increase at a rate proportional to payload weight as a percent of gross weight.

In relation to gross weight, the total-envelope shape factor is $4400^{2/3}/1530 = 0.177$. This factor also indicates potential gross weights above the chosen nominal values up to approximately 24 948 kilograms (55 000 pounds). The nominal value of 17 690 kilograms (39 000 pounds), therefore, is subject to an increase of greater than 25 percent. However, if the curve A values of figure 9 were used in the analysis, the comparable forecast would be for a growth of approximately 80 percent.

DEVELOPMENT OF DATA

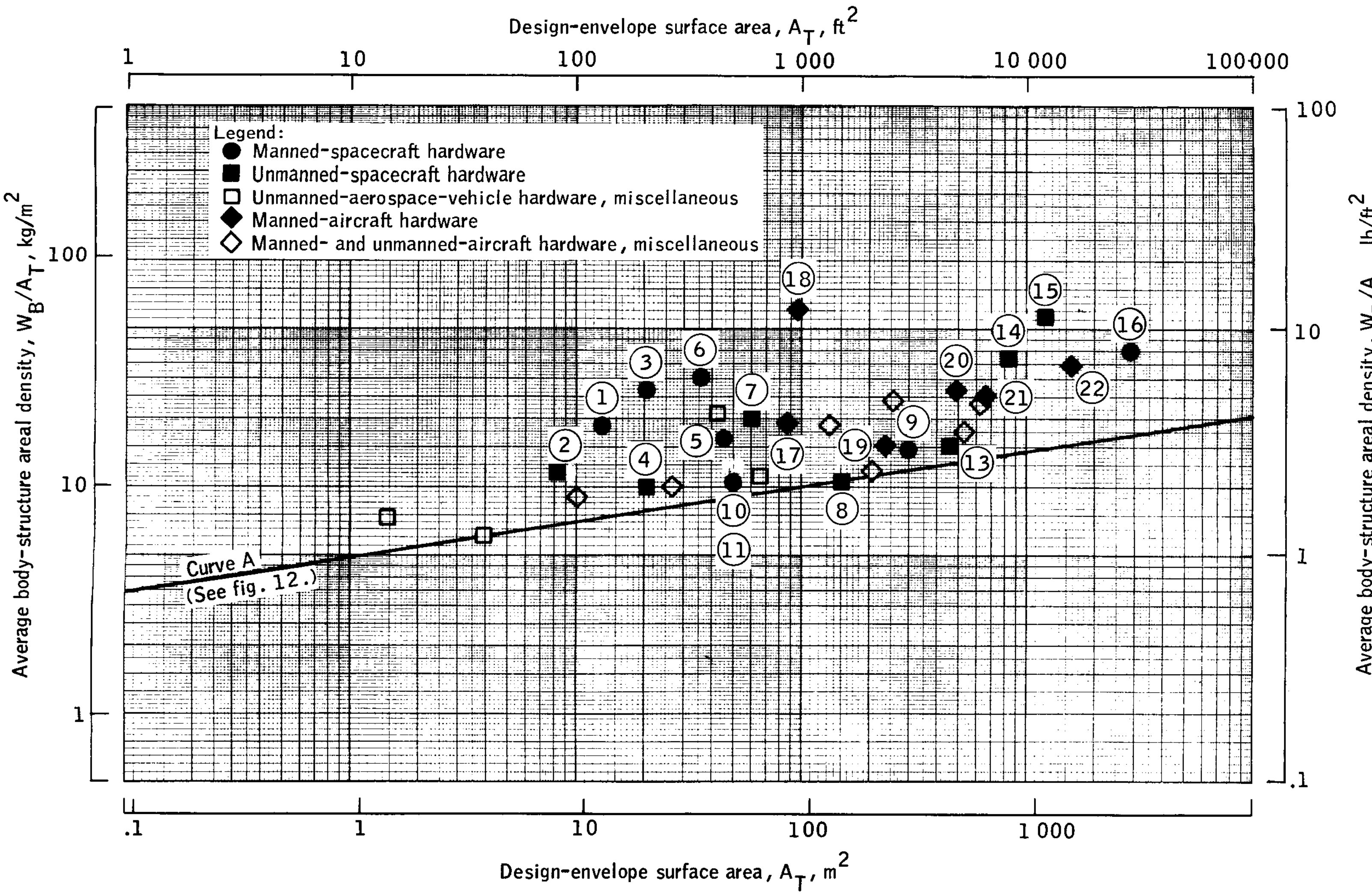
Weight Estimating

Generalized density relationships. - The data points and values used in the development of the original data are found in the appendix and are plotted in figure 13. The data points in figures 13, 14, and 15 are referenced to the figures in the appendix. A full logarithmic grid is used in figures 13, 14, and 15 so that a large selection of data can be used. The basic trend of decreasing average density with increasing design-envelope size (volume) is observed for gross weight and body-structure weight, both exclusive of induced environment protection (refs. 1 and 2).



Note: Data-point number designations refer to the column of the appendix figures that corresponds to the circled numbers listed in the line entitled "Key Data Points." Appropriate volume adjustments have been made for the deletion of code 3.0.

Figure 13. - Generalized density relationships.



Note: Data point number designations refer to the column of the appendix figures that corresponds to the circled numbers listed in the line entitled "Key Data Points." Weight and volume data are based on code 2.0 only of appendix.

Figure 14. - Generalized body-structure areal-density relationships.

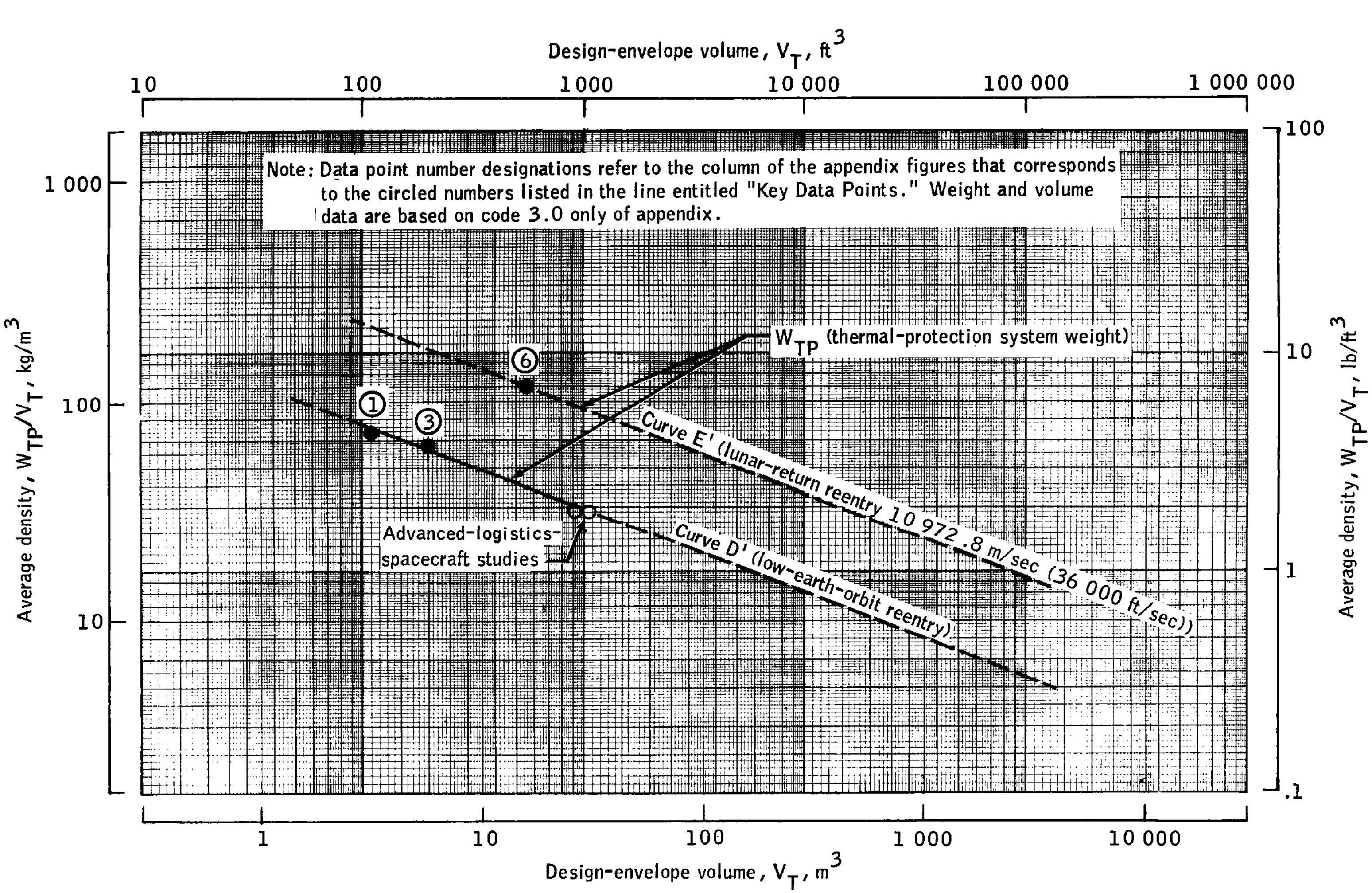


Figure 15.- Generalized induced-environment-protection (thermal protection) density relationships.

Minimum gross-weight density, manned modules. - The smallest manned body is represented by the Mercury spacecraft, which has approximately 50 percent of the volume pressurized; while the largest manned body is the C-5A aircraft, which has approximately 80 percent of the volume pressurized. Curve A (fig. 13) goes through conceptual design densities of both vehicles. The remainder of the manned-spacecraft data falls at various positions, but all data fall on or above curve A. Therefore, on the strength of the data shown, curve A represents a minimum practical gross-weight estimate for manned spacecraft in view of various estimating techniques and the corresponding allowances for volume and packaging.

Gross-weight density and propellant-to-gross-weight ratio. - Curve C of figure 13 is obtained by averaging the gross-weight densities and volumes of the densely packaged manned modules of Mercury, Gemini, and Apollo spacecraft and the B-58 aircraft cabin and by applying the same slope as curve A of figure 13. Therefore, an estimating band is obtained between curves A and C, and estimates at curve C are approximately 60 percent greater than estimates at curve A for any given volume. Existing vehicle data agree well with curve C (the maximum curve) for small values of V_T around 2.83 to 28.32 m^3 (100 to 1000 ft^3), and no data suggest that maximum weight growth is less than 60 percent for large values of V_T up to 2831.68 m^3 (100 000 ft^3). In figure 13, five data points from manned-spacecraft and space-station studies fall in this band. Therefore, this band should be reasonable for weight estimates for advanced manned spacecraft and space stations.

It seems logical that as W_P/W_G is increased for any V_T, the gross-weight density should increase. The data points between curves A and C in figure 13 indicate that W_P/W_G can range up to approximately 0.5. This statement is supported by essentially all of the data points above curve C which have a W_P/W_G greater than 0.5. The exceptions are some aircraft densities above curve C that have a W_P/W_G less than 0.5; however, these densities reflect significant weight penalties for wings, tails, and landing gear, which are not normally included for advanced manned spacecraft.

Curve B of figure 13 is the average between curves A and C. The Apollo lunar module ascent stage has a W_P/W_G of approximately 0.5 and a gross-weight density that coincides with curve B. As discussed previously in the section entitled "Techniques," constant W_P/W_G lines can be drawn for preliminary estimates of gross density. However, this can be done only if propellant bulk-density variations and propellant-volume-to-total-vehicle-volume ratios are sufficiently normalized. This technique of estimating gross densities needs more development, based on a more complete volume analysis.

Gross-weight density and shape factor. - A final basic indicator of packaging density is expressed in f_s, a nondimensional factor. Of all the manned spacecraft data shown, the Apollo command module has the highest f_s (0.181). The lowest f_s value is 0.125 for the C-5A aircraft body. These two vehicles (bodies) also have the highest and the lowest gross-weight densities, respectively.

The f_s scale shown in figure 13 is linked to weight growth. Vehicle-weight estimates tend to grow at rapid rates if the f_s is high (greater than 0.17). This statement is especially true if the original weight estimate is made below or on curve A of figure 13. Therefore, the gross-weight estimate should be made (in view of f_s) between curves A and C, with recognition of the gross-weight potential or constraint that the shape indicates. The preliminary range of f_s between curve A and the ultimate density expected for the Apollo command module (above curve C) is 0.125 to 0.181.

For cylindrical shapes, the maximum f_s occurs when the height is equal to the diameter (the nearest approximation to a sphere). Therefore, for given-diameter space stations, for example, reduced f_s will result in length-to-diameter ratios less than 1 as well as greater than 1. A few f_s values are as follows:

Mercury spacecraft	0.167
Gemini spacecraft	0.163
Apollo command module	0.181
Lunar module ascent stage	0.151
Subsystems test bed (STB)	0.174
Apollo spacecraft and Saturn IVB	0.141

A theory is advanced that the maximum density of manned spacecraft increases with increasing f_s for a given internal dry-weight loading. Although an appreciable difference in internal loadings exists among the Mercury spacecraft, the Gemini spacecraft, the Apollo command module, and the Apollo lunar module ascent stage, for example, the theory in general is upheld. This theory is strengthened when appropriate normalizations for body-structure weight are considered.

The assumption must be made, of course, that all manned spacecraft approach maximum density at the end of a program. This assumption appears to be valid, at least for the manned modules, which in several instances encountered appreciable difficulties in packaging and stowing. Designing for the maximum use of volume should be a prime criterion. Of equal importance are the allowances during the definition phase for size, shape, weight, and weight growth.

Body-structure weight based on volume. - Figure 13 also shows a trend of body structure, namely, decreasing average density in relation to increasing body size or volume. Curves A', B', and C' are derived visually in a manner similar to curves A, B, and C. The basic trend is similar to the gross-weight trend, but the average density decreases with increasing size at a lesser rate. The principal factor involved is that the body-structure weight (the container weight) depends more on the area, whereas the nonstructure weight (the contained weight) depends more on the volume. However, to make several comparisons to gross weight and body-structure weight and to minimize the number of basic estimating parameters for first approximations, the body-structure weight is shown here in terms of volume.

In general, body-structure densities between curves A' (minimum density, manned vehicles) and B' (average density, manned vehicles) of figure 13 are compatible with gross-weight densities between curves A and B. The main exceptions are the anticipated ultimate Apollo command module gross-weight density, the Apollo lunar module ascent-stage structure (in which only 33 percent of the volume is pressurized), and vehicles with a W_P/W_G greater than 0.5. Because the Apollo command module body-structure weight correlates well with curve C' of figure 13, the amount that the gross-weight density is expected to exceed curve C must be attributed to weights of the other subsystems.

Body-structure weight based on area. - Another basic trend of body structure is average areal density in relation to the design-envelope area. This trend is an increasing unit weight in kilograms per square meter (pounds per square foot) with increasing area in square meters (square feet), as shown in figures 12 and 14. The original data are shown in the appendix.

It is conceivable that a body can have a volume that approaches zero, but at the same time have a very large surface area. An estimate based on the volume would therefore underestimate the body-structure weight as this condition is approached, while an estimate based on the area would be more accurate. Also, because the body-structure-weight data of figures 12, 13, and 14 vary in relation to bookkeeping and reporting information on structural mounts and supports for equipment and so forth, the additional research and normalization involved in the area-based estimate provide the answer by a more accountable method than the volume-based estimate provides. Therefore, it is advisable to cross-check an estimate of body-structure weight based on volume against an estimate based on area.

It might be theorized that f_s could be a reasonable parameter for estimating body-structure weight. For large values of f_s, it must be assumed that the area has been minimized for any given volume. This minimization would indicate that the body-structure weight would also be minimized. However, it appears that in most cases with manned spacecraft, this assumption is not true; therefore, f_s has not been linked to estimation of body-structure weight, whether based on volume or area.

Induced environment-protection-system (thermal-protection system) weight. - Figure 15 presents a simplified approach for estimating the weight of the thermal-protection systems of reentry vehicles. The original data are found in the appendix. Data points 1 and 3 represent earth-orbit reentry, while data point 6 represents lunar-return reentry at a velocity of 10 972.8 m/sec (36 000 ft/sec). It is interesting to note that, in spite of appreciable differences in ablation-material density, heat-dissipation factor, area loading, body size, and body shape, a straight-line (on full-logarithmic grid) trend is obtained for data points 1 and 3 and for thoroughly analyzed study data. Data point 6 is extrapolated at the same slope for preliminary estimation purposes.

Manned spacecraft. - Not specifically shown in figure 13 are estimates for the weights of the total induced environment protection and the various nonstructure equipment subsystems and payload. However, the various nonstructure equipment subsystems and payload are implied in figure 13 within the gross-weight estimate. The principal constraining factors, regardless of the type and number of equipment subsystems and payloads, are the body size and shape. Perhaps unique in approach, it appears that this estimation technique should be applied early in a program, because the type and number of equipment subsystems and payloads are normally late inputs and because manned spacecraft tend to grow to maximum density.

The f_s scale is shown in figure 13 at the right of the gross-weight band of estimates. These data-based f_s values tentatively parallel curves A, B, and C of figure 13 and are general indicators of possible growth potential or packaging constraint (or both) for various configuration estimates. Trade-off analyses can be made visually between body-structure weight, gross weight, volume, shape factor, and weight growth (figs. 9 and 10).

Weight Forecasting

The inexorable weight growth of spacecraft must be anticipated, regardless of the estimate that is made in conceptual design and the ensuing program phases. A model curve of weight growth is difficult to develop, because it is affected by many factors not directly associated with the engineering aspects of weight technology. From the working curves presented in figures 9 and 12 and the data curves in figures 13, 14, and 15, it may be argued that a higher estimate than minimum or average would preclude large weight growths. To a certain extent, this is true, all other factors remaining equal. However, all the other factors do not remain equal from vehicle to vehicle and from program to program. The first likely variation with regard to a higher estimate than minimum or average would be the undesirable advantage taken of this estimate in early design, resulting in an overweight product from the beginning. Caution should be taken if a manned spacecraft is estimated below either curve A or curve A' (figs. 9 and 13). Unless this design-weight estimate can be justified by other acceptable means, it is subject to high rates of growth. Therefore, curves B and B' (figs. 9 and 13) are defined as being synonymous with the design-limit weight or with both the nominal and the maximum weight to be expected at a particular spacecraft operational condition and should be used to determine analytically or experimentally all weight-dependent performance. Design-limit weights anticipate weight growth throughout the program, but will never reflect the actual weight of any element until its operational status is reached.

The weight growth represented between curves A and C of figures 9 and 13 is approximately 60 percent. Until more spacecraft are built and the resulting data are factored into the presented estimating procedure, it is doubtful that this percentage can be substantially reduced. Some improvement may result when the ratios of propellant weight to gross weight and of propellant volume are applied to existing information.

Propellant-to-gross-weight ratio. - One of the earliest and perhaps relatively most predictable weight allowances for spacecraft is the propellant, which is a prime performance indicator. Based on essentially all the data examined, the most serious weight growth occurred on the dry weight of the vehicles. Although the propellant weight did increase in many instances, the propellant-to-gross-weight ratio remained fairly constant throughout the programs. This observation reflects an attempt to maintain constant or improved performance to offset the increased dry weight.

Weight-growth pattern. - The area in which the program weight-growth pattern is most likely to be affected is shown in figure 16 (between curves I and III). The Mercury spacecraft, the Apollo command module, and the Apollo lunar module ascent stage fall within this corridor of weight growth. The Apollo lunar module ascent stage represents the highest propellant-to-gross-weight ratio (0.5). The Gemini weight growth falls below this corridor, and, based on the relative (to Mercury) original estimates, Gemini apparently reflects the learning-factor effect and is considered a second-generation vehicle.

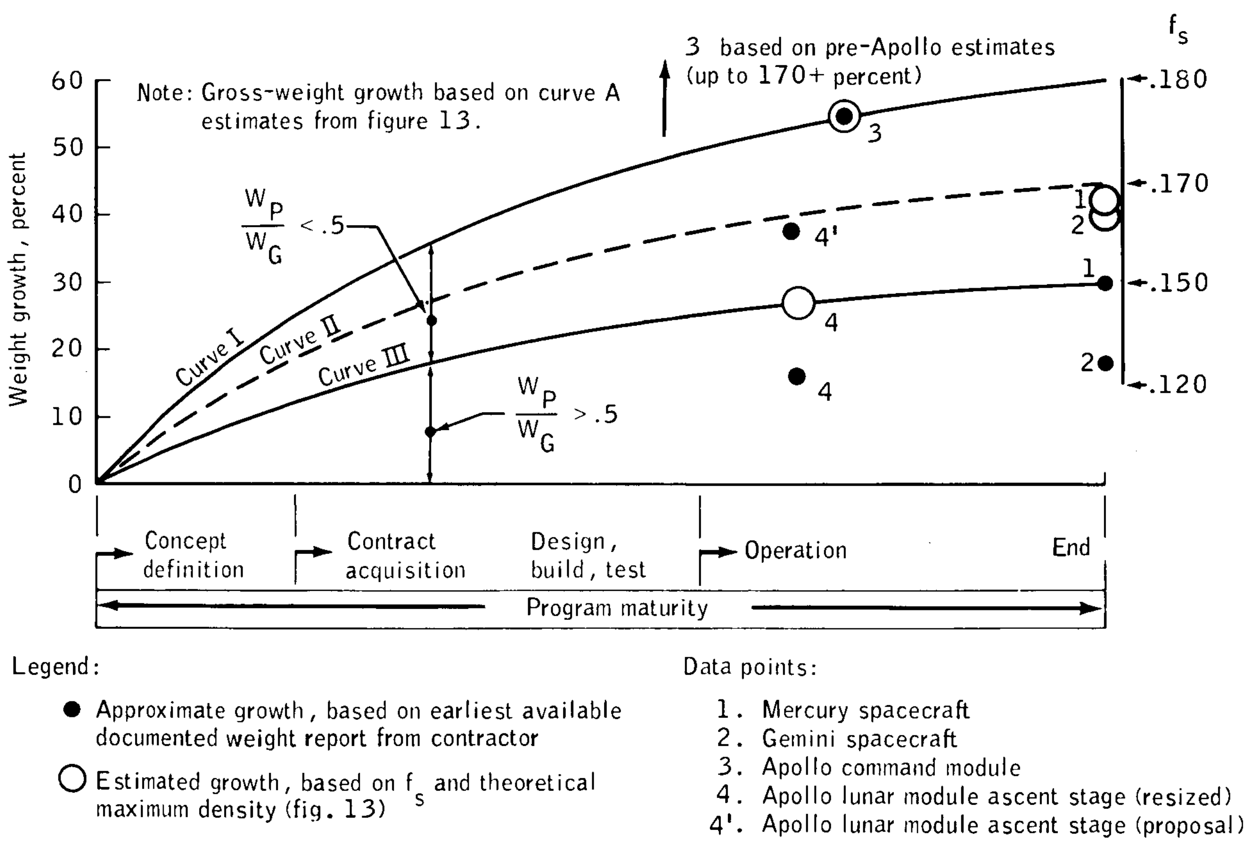


Figure 16. - Weight-growth-forecast curves for first-generation vehicles.

Relationship of the Estimate to the Forecast

The curve A estimates of figures 9 and 13 have been recommended as minimum weight-estimate values for advanced manned spacecraft and space stations. It is important to point out how these estimates, if applied to manned spacecraft from Project Mercury, the Gemini Program, and the Apollo Program, relate to the recommended forecasts.

If a manned spacecraft the size and shape of the Mercury spacecraft is estimated at curve A of figure 13, the W_G/V_T is approximately 288 kg/m^3 (18 lb/ft^3) at a V_T of approximately 2.83 m^3 (100 ft^3). Therefore, W_G is 816 kilograms (1800 pounds). The f_s of the Mercury spacecraft is 0.167; based on figure 16, a 42-percent growth is forecast for the W_G. The actual total weight growth (final flight) was 30 percent.

Similarly, if a manned spacecraft the size and shape of the Gemini spacecraft is estimated at curve A, the W_G/V_T is 184 kg/m^3 (11.5 lb/ft^3) at a V_T of 17.56 m^3 (620 ft^3), and W_G is 3234 kilograms (7130 pounds). The f_s of the Gemini spacecraft is 0.163; from figure 16, a 40-percent growth would be forecast. The actual total weight growth was 18 percent. The growth forecast is considerably more than that actually experienced; however, it should be noted in figure 13 that the Gemini adapter module (key data point 4) is considerably below curve A density and had the theoretical potential to grow considerably more than it did.

The Apollo command module V_T of 13.59 m^3 (480 ft^3) indicates a gross-weight density of 192 kg/m^3 (12 lb/ft^3) at curve A of figure 13. The resulting W_G is 2613 kilograms (5760 pounds), and the f_s of 0.181 suggests that the growth forecast should be 60 percent. The actual total weight growth of the Apollo command module was approximately 50 percent.

The manned Apollo lunar module ascent stage has a V_T of 21.24 m^3 (750 ft^3), which indicates a W_G/V_T of approximately 173 kg/m^3 (10.8 lb/ft^3) from curve A in figure 13. The resulting W_G is 3674 kilograms (8100 pounds), and from figure 16, an f_s of 0.151 indicates that the weight growth should be 30 percent. Based on the current weight of the Apollo lunar module ascent stage, this is an accurate forecast.

All of the preceding estimates were based on curve A of figure 13 to illustrate better what has happened on past manned spacecraft when size and shape were used as the main parameters. However, curve B is recommended for estimating the weights of advanced manned spacecraft, so that weight growth is at least anticipated. Values below this curve are more subject to a generally higher program weight-growth pattern.

CONCLUSIONS

All engineering technologies advance with time and knowledge. The advancement in weight technology is typified by advancements in structure that produce increasing strength-to-weight ratios and by other advancements from other disciplines that enable lightweight design. It might seem that the weight technology that deals with weight estimating and forecasting would also improve; however, this has not been the case.

In the same sense that technology in general has advanced, weight estimating has improved considerably. Sophisticated computer-aided techniques provide the most up-to-date methods of weight estimating. However, several fundamental observations are not now sufficiently considered and treated by these estimating techniques.

1. Because of weight growth, all estimating techniques and methods used for manned spacecraft thus far have underestimated the weight.

2. The time and design criteria are of extreme importance in advanced-design weight estimating. When it is determined quantitatively and qualitatively what design criteria are applicable, it is usually too late to be beneficial.

3. All aerospace vehicles tend to grow to maximum density. Other advancing technologies provide lightweight, more efficiently packaged, space-qualified hardware that can perform more functions that ever before; therefore, more functions and weight can be packaged within a given volume than ever before. The result of improved packaging technology is an underestimation of total density and thus of weight.

4. To advance weight technology realistically, the preceding observations must be studied methodically, historically, and uniformly from concept through operation. Recording and reporting techniques must be uniformly efficient to phase new weight information into an evolving status of a vehicle or program (or both). The status of the weight-engineering discipline must be raised to at least the status of the other typically competing disciplines of cost, performance, safety, structures, and so forth.

Thus, these four observations could contribute significantly to the overall advancement of weight technology.

The following more specific conclusions can be drawn from the information presented in this report.

1. The average estimating curves presented should help to offset a significant portion of the apparent underestimation of growth potential based on past manned spacecraft.

2. The theory that the shape factor is an index to maximum-density gross weight (zero growth potential) is strengthened by all the manned-spacecraft hardware data examined.

3. The theory that the shape factor is an index to body-structure weight efficiency is not wholly upheld by the manned-spacecraft hardware data examined.

4. It was revealed during this study that a fairly logical general pattern is established between structural weight density (body and total structure) and shape factor for all vehicles. The design-envelope volumes having the largest shape-factor values also reflect the lowest structure weight densities and vice versa. Although this general inverse relationship is established for structure weight based on structures ranging from the efficiently shaped bodies of unmanned and manned aerospace vehicles to the poorly shaped total structures of aircraft, the growth of gross weight appears to occur in direct relation to the shape-factor value.

5. Packaging technology for increasing size and variously shaped manned aerospace vehicles presents a potential problem area for weight estimates of future-generation vehicles.

6. More data normalization, including bookkeeping and reporting standardization, should improve basic estimating techniques and narrow the choice of an estimate for concept and study weights.

7. The cost and weight factors of manned spacecraft seem to increase at rates proportional to vehicle complexity and weight growth. More precise weight estimates are required to improve the cost and weight interdisciplinary relationships.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, January 27, 1971
975-11-89-00-72

REFERENCES

1. Anon.: Mass Properties Control Requirements for Missile and Space Vehicles. MIL-M-38310A (USAF), July 15, 1966.

2. Seccomb, M. L.: Apollo Program: Mass Properties Standard. NASA SP-6004, June 1, 1965.

3. Anon.: Weight and Balance Control Data (for Airplanes and Rotorcraft). Part I, Group Weight Statement, AN-9103-D. MIL-W-25140(ASG), Mar. 31, 1955.

APPENDIX

KEY DATA POINTS

The Spacecraft Summary Weight Statements (MSC Form 1522B) (figs. A-1 to A-6) show the key data that were used in the development of the various curves of this report. An attempt has been made to code all data according to the functional code of appendix B of reference 1.

After several years of advanced-design weight engineering on manned spacecraft and space stations, it became apparent that a form such as the Spacecraft Summary Weight Statement would help resolve many basic problems associated with weight breakdowns. The principal problem appeared to be nonconformity with and arbitrary deviation from the coding system used in reference 1, even at the first-generation level of breakdown.

The Spacecraft Summary Weight Statements show all of the 27 first-generation functional codes of reference 1 in line form. The eight columns can be identified by item, module, or spacecraft. Therefore, this form allows the summarized integration of code, system, item or module, and spacecraft at a single visual inspection.

It should be recognized that the values shown in the Spacecraft Summary Weight Statement are inherently subject to the limitations of data availability at various dates and to the decoding and recoding from other breakdowns of aircraft, spacecraft, and space stations. Also, the applicability of transferring aircraft data from form AN-9103-D (ref. 3) to the Spacecraft Summary Weight Statement is somewhat questionable. However, it appeared to be simpler and more meaningful to make such a transformation, as opposed to an opposite transformation. Moreover, relatively fewer aircraft data than spacecraft data are used.

The data points shown in figures 13, 14, and 15 are keyed to the data presented in figures A-1 to A-6. The numbers associated with the data points in figures 13, 14, and 15 refer to the information given in the particular column of figures A-1 to A-6 where the corresponding circled number is located. The circled numbers in figures A-1 to A-6 are found in the line entitled "Key Data Points."

SPACECRAFT SUMMARY WEIGHT STATEMENT

CONFIGURATION	BY	DATE
Mercury Spacecraft (similar to spacecraft 13)	Mass Properties Section	1963

CODE	SYSTEM	ITEM OR MODULE A	B	C	D	E	F	SPACECRAFT M	U
1.0	Aerodynamic Surfaces								
2.0	Body Structure	99	169	84				352	
3.0	Induced Envir Prot	10	218					228	
4.0	Lnch Recov & Dkg		159					159	
5.0	Main Propulsion	161	69					230	
6.0	Orient Control Sep & Ull		105					105	
7.0	Prime Power Source		92					92	
8.0	Power Conv & Distr	8	55	2				65	
9.0	Guidance & Navigation								
10.0	Instrumentation		55					55	
11.0	Communication		51					51	
12.0	Environmental Control		58					58	
13.0	(Reserved)								
14.0	Personnel Provisions		32					32	
15.0	Crew Sta Contrl & Pan		52					52	
16.0	Range Safety & Abort								
SUBTOTALS (Dry Weight)		278	1115	86				1479	
17.0	Personnel		109					109	
18.0	Cargo								
19.0	Ordnance								
20.0	Ballast	84	19					103	
21.0	Resid Prop & Serv Items		2					2	
SUBTOTALS (Inert Weight)		362	1245	86				1603	
22.0	Res Prop & Serv Items								
23.0	Inflight Losses		14					14	
24.0	Thrust Decay Propellant								
25.0	Full Thrust Propellant	133	91					224	
26.0	Thrust Prop Buildup								
27.0	Pre-Ignition Losses								
	Actual Weight Adjustment		8					8	
	Key Data Points		1	2					
TOTAL (Gross Weight) (kg)		495	1358	86				1939	
Design Envelope Volume (m^3)			3.11	3.34					
Pressurized Volume (m^3)			1.42						
Design Envel Surf Area (m^2)			12.91	a7.43					
Pressurized Surf Area (m^2)									
Design q, Max (kg/m^2)									
Design g, Max			15						
Design Power, Max (KW)									
Design No. Men Days			1/3						

DESIGNATIONS:

Code, System; Ref. MIL-M-38310A or SP-6004

Item or Module

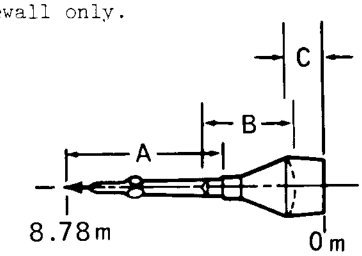
- A Launch Escape System
- B Reentry Module 1
- C Adapter 2
- D
- E
- F

Spacecraft

- M Manned Launch A+B+C
- U Unmanned Launch

NOTES & SKETCHES:

[a] Sidewall only.



(a) International System of Units (SI Units).

Figure A-1. - Spacecraft Summary Weight Statement for Mercury spacecraft.

SPACECRAFT SUMMARY WEIGHT STATEMENT

CONFIGURATION	BY	DATE
Mercury Spacecraft (similar to spacecraft 13)	Mass Properties Section	1963

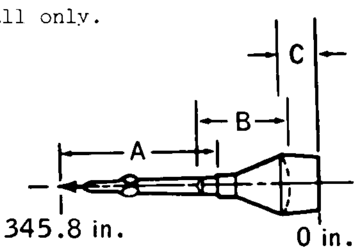
CODE	SYSTEM	ITEM OR MODULE A	B	C	D	E	F	SPACECRAFT M	U
1.0	Aerodynamic Surfaces								
2.0	Body Structure	218	375	185				778	
3.0	Induced Envir Prot	22	480					502	
4.0	Lnch Recov & Dkg		350					350	
5.0	Main Propulsion	356	153					509	
6.0	Orient Control Sep & Ull		231					231	
7.0	Prime Power Source		202					202	
8.0	Power Conv & Distr	18	122	5				145	
9.0	Guidance & Navigation								
10.0	Instrumentation		121					121	
11.0	Communication		113					113	
12.0	Environmental Control		128					128	
13.0	(Reserved)								
14.0	Personnel Provisions		70					70	
15.0	Crew Sta Contrl & Pan		114					114	
16.0	Range Safety & Abort								
SUBTOTALS (Dry Weight)		614	2459	190				3263	
17.0	Personnel		240					240	
18.0	Cargo								
19.0	Ordnance								
20.0	Ballast	185	41					226	
21.0	Resid Prop & Serv Items		5					5	
SUBTOTALS (Inert Weight)		799	2745	190				3734	
22.0	Res Prop & Serv Items								
23.0	Inflight Losses		31					31	
24.0	Thrust Decay Propellant								
25.0	Full Thrust Propellant	293	200					493	
26.0	Thrust Prop Buildup								
27.0	Pre-Ignition Losses								
	Actual Weight Adjustment		18					18	
	Key Data Points		1	2					
TOTAL (Gross Weight) (Lb)		1092	2994	190				4276	
Design Envelope Volume (Ft^3)			110	119					
Pressurized Volume (Ft^3)			50						
Design Envel Surf Area (Ft^2)			139	[a]80					
Pressurized Surf Area (Ft^2)									
Design q, Max (Lb/Ft^2)									
Design g, Max			15						
Design Power, Max (KW)									
Design No. Men/Days			1/3						

DESIGNATIONS:

Code, System; Ref. MIL-M-38310A or SP-6004	
Item or Module	
A	Launch Escape System
B	Reentry Module (1)
C	Adapter (2)
D	
E	
F	
Spacecraft	
M Manned Launch	A+B+C
U Unmanned Launch	

NOTES & SKETCHES:

[a]Sidewall only.



(b) Customary U. S. Units.

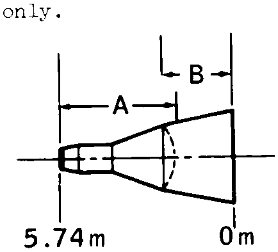
Figure A-1. - Concluded.

SPACECRAFT SUMMARY WEIGHT STATEMENT									
CONFIGURATION Gemini Spacecraft (2-day orbital rendezvous)		BY Mass Properties Section				DATE June 1, 1965			
CODE	SYSTEM	ITEM OR MODULE						SPACECRAFT	
		A	B	C	D	E	F	M	U
1.0	Aerodynamic Surfaces								
2.0	Body Structure	487	188					675	
3.0	Induced Envir Prot	332						332	
4.0	Lnch Recov & Dkg	160						160	
5.0	Main Propulsion		65					65	
6.0	Orient Control Sep & Ull	82	185					267	
7.0	Prime Power Source	52	191					243	
8.0	Power Conv & Distr	71	23					94	
9.0	Guidance & Navigation	123						123	
10.0	Instrumentation	85	49					134	
11.0	Communication	27	14					41	
12.0	Environmental Control	136	132					268	
13.0	(Reserved)								
14.0	Personnel Provisions	276	4					280	
15.0	Crew Sta Contrl & Pan	59						59	
16.0	Range Safety & Abort								
SUBTOTALS (Dry Weight)		1890	851					2741	
17.0	Personnel	189						189	
18.0	Cargo								
19.0	Ordnance	12	5					17	
20.0	Ballast	67						67	
21.0	Resid Prop & Serv Items								
SUBTOTALS (Inert Weight)		2158	856					3014	
22.0	Res Prop & Serv Items								
23.0	Inflight Losses	15	41					56	
24.0	Thrust Decay Propellant								
25.0	Full Thrust Propellant	34	416					450	
26.0	Thrust Prop Buildup								
27.0	Pre-Ignition Losses								
Actual Weight Adjustment		-2	1					-1	
Key Data Points		3	4					5	
TOTAL (Gross Weight) (kg)		2205	1314					3519	
Design Envelope Volume (m^3)		5.61	12.60					17.75	
Pressurized Volume (m^3)		2.27							
Design Envel Surf Area (m^2)		20.16	[a]19.32					41.62	
Pressurized Surf Area (m^2)									
Design q, Max (kg/m^2)									
Design g, Max		15							
Design Power, Max (KW)									
Design No. Men/Days								2/2	

DESIGNATIONS:	
Code, System; Ref. MIL-M-38310A or SP-6004	
Item or Module	
A Reentry Module	3
B Adapter Module	4
C	
D	
E	
F	
Spacecraft	
M Manned Launch A+B	5
U Unmanned Launch	

NOTES & SKETCHES:

[a]Sidewall only.



(a) International System of Units (SI Units).

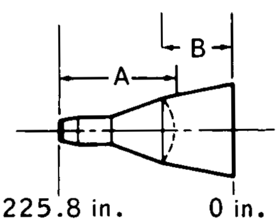
Figure A-2. - Spacecraft Summary Weight Statement for Gemini spacecraft.

SPACECRAFT SUMMARY WEIGHT STATEMENT									
CONFIGURATION Gemini Spacecraft (2-day orbital rendezvous)			BY Mass Properties Section				DATE June 1, 1965		
CODE	SYSTEM	ITEM OR MODULE						SPACECRAFT	
		A	B	C	D	E	F	M	U
1.0	Aerodynamic Surfaces								
2.0	Body Structure	1073	417					1490	
3.0	Induced Envir Prot	731						731	
4.0	Lnch Recov & Dkg	352						352	
5.0	Main Propulsion		143					143	
6.0	Orient Control Sep & Ull	181	407					588	
7.0	Prime Power Source	114	421					535	
8.0	Power Conv & Distr	157	51					208	
9.0	Guidance & Navigation	272						272	
10.0	Instrumentation	188	108					296	
11.0	Communication	60	30					90	
12.0	Environmental Control	300	290					590	
13.0	(Reserved)								
14.0	Personnel Provisions	610	8					618	
15.0	Crew Sta Contrl & Pan	129						129	
16.0	Range Safety & Abort								
SUBTOTALS (Dry Weight)		4167	1875					6042	
17.0	Personnel	416						416	
18.0	Cargo								
19.0	Ordnance	27	12					39	
20.0	Ballast	148						148	
21.0	Resid Prop & Serv Items								
SUBTOTALS (Inert Weight)		4758	1887					6645	
22.0	Res Prop & Serv Items								
23.0	Inflight Losses	34	91					125	
24.0	Thrust Decay Propellant								
25.0	Full Thrust Propellant	75	916					991	
26.0	Thrust Prop Buildup								
27.0	Pre-Ignition Losses								
Actual Weight Adjustment		-6	3					-3	
Key Data Points		3	4					5	
TOTAL (Gross Weight) (Lb)		4861	2897					7758	
Design Envelope Volume (Ft3)		198	448					627	
Pressurized Volume (Ft3)		80							
Design Envel Surf Area (Ft2)		217	[a]208					448	
Pressurized Surf Area (Ft2)									
Design q, Max (Lb/Ft2)									
Design g, Max		15							
Design Power, Max (KW)									
Design No. Men/Days								2/2	

DESIGNATIONS:		
Code, System; Ref. MIL-M-38310A or SP-6004		
Item or Module		
A	Reentry Module	3
B	Adapter Module	4
C		
D		
E		
F		
Spacecraft		
M	Manned Launch A+B	5
U	Unmanned Launch	

NOTES & SKETCHES

[a]Sidewall only.



(b) Customary U.S. Units.

Figure A-2. - Concluded.

SPACECRAFT SUMMARY WEIGHT STATEMENT

CONFIGURATION	BY	DATE
Apollo Spacecraft 106	Mass Properties Section	May 1, 1968

CODE	SYSTEM	ITEM OR MODULE A	B	C	D	E	F	SPACECRAFT M	U
1.0	Aerodynamic Surfaces	146						146	
2.0	Body Structure	500	954	1 112	1 438			4 004	
3.0	Induced Envir Prot	453	1 757	241	46			2 497	
4.0	Lnch Recov & Dkg		438					438	
5.0	Main Propulsion	740		1 248				1 988	
6.0	Orient Control Sep & Ull	270	139	206				615	
7.0	Prime Power Source		143	583				726	
8.0	Power Conv & Distr	33	494	204	36			767	
9.0	Guidance & Navigation		270					270	
10.0	Instrumentation		19	33				52	
11.0	Communication		137	67				204	
12.0	Environmental Control		251	100				351	
13.0	(Reserved)								
14.0	Personnel Provisions		191					191	
15.0	Crew Sta Contrl & Pan		180					180	
16.0	Range Safety & Abort								
SUBTOTALS (Dry Weight)		2 142	4 973	3 794	1 520			12 429	
17.0	Personnel		488					488	
18.0	Cargo (fig. A-4(a))				14 745			14 745	
19.0	Ordnance	20	15	24	200			259	
20.0	Ballast	435						435	
21.0	Resid Prop & Serv Items		63	466				529	
SUBTOTALS (Inert Weight)		2 597	5 539	4 284	16 465			28 885	
22.0	Res Prop & Serv Items								
23.0	Inflight Losses	4	124	930				1 058	
24.0	Thrust Decay Propellant								
25.0	Full Thrust Propellant	1 442		[a]18 026				19 468	
26.0	Thrust Prop Buildup								
27.0	Pre-Ignition Losses								
	Actual Weight Adjustment								
	Key Data Points		6	7	8			9	
TOTAL (Gross Weight) (kg)		4 043	5 663	23 240	16 465			49 411	
Design Envelope Volume (m^3)		6.00	15.74	55.78	185.19			260.57	
Pressurized Volume (m^3)			10.36		7.08			17.44	
Design Envel Surf Area (m^2)		27.87	35.02	[b]56.95	[b]140.75			283.73	
Pressurized Surf Area (m^2)									
Design q, Max (kg/m^2)									
Design g, Max			20						
Design Power, Max (KW)									
Design No. Men/Days								3/10	

DESIGNATIONS:

Code, System; Ref. MIL-M-38310A or SP-6004

Item or Module

- A Launch Escape System
- B Command Module 6
- C Service Module 7
- D Adapter and Lunar Module 8
- E
- F

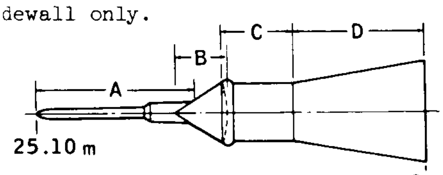
Spacecraft

- M Manned Launch A+B+C+D 9
- U Unmanned Launch

NOTES & SKETCHES:

[a]Usable capacity based on DZ-118078-3E, Oct. 1968.

[b]Sidewall only.



(a) International System of Units (SI Units).

Figure A-3. - Spacecraft Summary Weight Statement for Apollo spacecraft 106.

SPACECRAFT SUMMARY WEIGHT STATEMENT

CONFIGURATION	BY	DATE
Apollo Spacecraft 106	Mass Properties Section	May 1, 1968

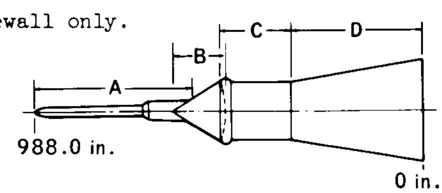
CODE	SYSTEM	ITEM OR MODULE						SPACECRAFT	
		A	B	C	D	E	F	M	U
1.0	Aerodynamic Surfaces	323						323	
2.0	Body Structure	1 102	2 103	2 452	3 170			8 827	
3.0	Induced Envir Prot	998	3 874	532	100			5 504	
4.0	Lnch Recov & Dkg		965					965	
5.0	Main Propulsion	1 631		2 751				4 382	
6.0	Orient Control Sep & Ull	596	307	454				1 357	
7.0	Prime Power Source		315	1 285				1 600	
8.0	Power Conv & Distr	73	1 090	450	79			1 692	
9.0	Guidance & Navigation		595					595	
10.0	Instrumentation		42	74				116	
11.0	Communication		301	147	1			449	
12.0	Environmental Control		553	220				773	
13.0	(Reserved)								
14.0	Personnel Provisions		422					422	
15.0	Crew Sta Contrl & Pan		396					396	
16.0	Range Safety & Abort								
SUBTOTALS (Dry Weight)		4 723	10 963	8 365	3 350			27 401	
17.0	Personnel		1 075					1 075	
18.0	Cargo (fig. A-4(b))				32 508			32 508	
19.0	Ordnance	45	33	52	441			571	
20.0	Ballast	958						958	
21.0	Resid Prop & Serv Items		140	1 027				1 167	
SUBTOTALS (Inert Weight)		5 726	12 211	9 444	36 299			63 680	
22.0	Res Prop & Serv Items								
23.0	Inflight Losses	9	274	2 050				2 333	
24.0	Thrust Decay Propellant								
25.0	Full Thrust Propellant	3 178		[a]39 741				42 919	
26.0	Thrust Prop Buildup								
27.0	Pre-Ignition Losses								
	Actual Weight Adjustment								
	Key Data Points		6	7	8			9	
TOTAL (Gross Weight) (Lb)		8 913	12 485	51 235	36 299			108932	
Design Envelope Volume (Ft^3)		212	556	1 970	6 540			9 202	
Pressurized Volume (Ft^3)			366		250			616	
Design Envel Surf Area (Ft^2)		300	377	[b]613	[b]1 515			3 054	
Pressurized Surf Area (Ft^2)									
Design q, Max (Lb/Ft^2)									
Design g, Max			20						
Design Power, Max (KW)									
Design No. Men/Days								3/10	

DESIGNATIONS:		
Code, System: Ref. MIL-M-38310A or SP-6004		
Item or Module		
A	Launch Escape System	
B	Command Module	6
C	Service Module	7
D	Adapter and Lunar Module	8
E		
F		
Spacecraft		
M	Manned Launch A+B+C+D	9
U	Unmanned Launch	

NOTES & SKETCHES:

[a]Usable capacity based on DZ-118078-3E, Oct. 1968.

[b]Sidewall only.



(b) Customary U.S. Units.

Figure A-3. - Concluded.

SPACECRAFT SUMMARY WEIGHT STATEMENT

CONFIGURATION: Apollo Lunar Module

BY: Mass Properties Section

DATE: January 1969

CODE	SYSTEM	ITEM OR MODULE A	B	C	D	E	F	SPACECRAFT M	U
1.0	Aerodynamic Surfaces								
2.0	Body Structure	473	443					916	
3.0	Induced Envir Prot	155	149					304	
4.0	Lnch Recov & Dkg	23	218					241	
5.0	Main Propulsion	213	505					718	
6.0	Orient Control Sep & Ull	156	6					162	
7.0	Prime Power Source	167	260					427	
8.0	Power Conv & Distr	211	30					241	
9.0	Guidance & Navigation	35	20					55	
10.0	Instrumentation	58	3					61	
11.0	Communication	50	6					56	
12.0	Environmental Control	132	44					176	
13.0	(Reserved) G.F.E.[a]	277	150					427	
14.0	Personnel Provisions	44	24					68	
15.0	Crew Sta Contrl & Pan	109	1					110	
16.0	Range Safety & Abort								
SUBTOTALS (Dry Weight)		2 103	1 859					3 962	
17.0	Personnel								
18.0	Cargo								
19.0	Ordnance	12	12					24	
20.0	Ballast								
21.0	Resid Prop & Serv Items	54	122					176	
SUBTOTALS (Inert Weight)		2 169	1 993					4 162	
22.0	Res Prop & Serv Items								
23.0	Inflight Losses	314	148					462	
24.0	Thrust Decay Propellant								
25.0	Full Thrust Propellant	2 258	7 863					10 121	
26.0	Thrust Prop Buildup								
27.0	Pre-Ignition Losses								
	Actual Weight Adjustment								
	Key Data Points	10	11					12	
TOTAL (Gross Weight) (kg)		4 741	10 004					14 745	
Design Envelope Volume (m^3)		21.24	24.07						
Pressurized Volume (m^3)		7.08							
Design Envel Surf Area (m^2)		51.10	51.10						
Pressurized Surf Area (m^2)									
Design q, Max (kg/m^2)									
Design g, Max									
Design Power, Max (KW)									
Design No. Men/Days								2/2	

DESIGNATIONS:

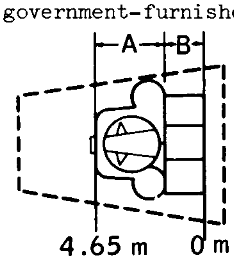
Code, System; Ref. MIL-M-38310A or SP-6004

Item or Module
- A Ascent stage 10
- B Descent stage 11
- C
- D
- E
- F

Spacecraft
- M Manned Launch A+B (fig. A-3(a)) 12
- U Unmanned Launch

NOTES & SKETCHES:

[a] G.F.E. is government-furnished equipment.



(a) International System of Units (SI Units).

Figure A-4. - Spacecraft Summary Weight Statement for Apollo lunar module.

SPACECRAFT SUMMARY WEIGHT STATEMENT

CONFIGURATION	BY	DATE
Apollo Lunar Module	Mass Properties Section	January 1969

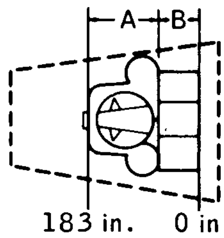
CODE	SYSTEM	ITEM OR MODULE A	B	C	D	E	F	SPACECRAFT M	U
1.0	Aerodynamic Surfaces								
2.0	Body Structure	1 042	978					2 020	
3.0	Induced Envir Prot	342	328					670	
4.0	Lnch Recov & Dkg	50	480					530	
5.0	Main Propulsion	469	1 113					1 582	
6.0	Orient Control Sep & Ull	344	13					357	
7.0	Prime Power Source	369	573					942	
8.0	Power Conv & Distr	464	67					531	
9.0	Guidance & Navigation	78	43					121	
10.0	Instrumentation	128	7					135	
11.0	Communication	111	13					124	
12.0	Environmental Control	291	97					388	
13.0	(Reserved) G.F.E.[a]	610	331					941	
14.0	Personnel Provisions	98	53					151	
15.0	Crew Sta Contrl & Pan	239	3					242	
16.0	Range Safety & Abort								
SUBTOTALS (Dry Weight)		4 635	4 099					8 734	
17.0	Personnel								
18.0	Cargo								
19.0	Ordnance	26	26					52	
20.0	Ballast								
21.0	Resid Prop & Serv Items	120	270					390	
SUBTOTALS (Inert Weight)		4 781	4 395					9 176	
22.0	Res Prop & Serv Items								
23.0	Inflight Losses	693	326					1 019	
24.0	Thrust Decay Propellant								
25.0	Full Thrust Propellant	4 979	17 334					22 313	
26.0	Thrust Prop Buildup								
27.0	Pre-Ignition Losses								
	Actual Weight Adjustment								
	Key Data Points	10	11					12	
TOTAL (Gross Weight) (Lb)		10 453	22 055					32 508	
Design Envelope Volume (Ft^3)		750	850						
Pressurized Volume (Ft^3)		250							
Design Envel Surf Area (Ft^2)		550	550						
Pressurized Surf Area (Ft^2)									
Design q, Max (Lb/Ft^2)									
Design g, Max									
Design Power, Max (KW)									
Design No. Men/Days								2/2	

DESIGNATIONS:

Code, System; Ref. MIL-M-38310A or SP-6004		
Item or Module		
A	Ascent stage	10
B	Descent stage	11
C		
D		
E		
F		
Spacecraft		
M	Manned Launch A+B (fig. A-3(b))	12
U	Unmanned Launch	

NOTES & SKETCHES:

[a]G.F.E. is government-furnished equipment.



(b) Customary U. S. Units.

Figure A-4. - Concluded.

SPACECRAFT SUMMARY WEIGHT STATEMENT										
CONFIGURATION Saturn V-Apollo			BY Mass Properties Section				DATE August 1966			
CODE	SYSTEM	ITEM OR MODULE						SPACECRAFT		
		A	B	C	D	E	F	M	U
1.0	Aerodynamic Surfaces	146		146			932	1 078	
2.0	Body Structure	4 004	916	4 920	6 208	28 199	63 552	102 879	
3.0	Induced Envir Prot	2 497	304	2 801				2 801	
4.0	Lnch Recov & Dkg	438	241	679				679	
5.0	Main Propulsion	1 988	718	2 706	2 799	11 858	63 281	80 644	
6.0	Orient Control Sep & Ull	615	162	777	792	1 034	290	2 893	
7.0	Prime Power Source	726	427	1 153	978	395	430	3 964	
8.0	Power Conv & Distr	767	241	1 008					
9.0	Guidance & Navigation	270	55	325	292		26	643	
10.0	Instrumentation	52	61	113	852	2 010	1 542	4 517	
11.0	Communication	204	56	260				260	
12.0	Environmental Control	351	176	527	432	544	151	1 654	
13.0	(Reserved) G.F.E.[a]		427	427				427	
14.0	Personnel Provisions	191	68	259				259	
15.0	Crew Sta Contrl & Pan	180	110	290				290	
16.0	Range Safety & Abort				33	128	182	343	
SUBTOTALS (Dry Weight)		12 429	3 962	16 391	12 386	44 168	130386	203 331	
17.0	Personnel	488		488				488	
18.0	Cargo								
19.0	Ordnance	259	24	283	52	379	1 100	1 814	
20.0	Ballast	435		435				435	
21.0	Resid Prop & Serv Items	529	176	705	408	2 356	14 380	17 849	
SUBTOTALS (Inert Weight)		14 140	4 162	18 302	12 846	46 903	145866	223 917	
22.0	Res Prop & Serv Items				428	819	9 707	10 954	
23.0	Inflight Losses	1 058	462	1 520	2 031	1 708		5 259	
24.0	Thrust Decay Propellant				85	182	803	1 070	
25.0	Full Thrust Propellant	19 468	10 121	29 589	104 349	439 985	2085736	2659659	
26.0	Thrust Prop Buildup				331	1 091	39 871	41 293	
27.0	Pre-Ignition Losses								
	Actual Weight Adjustment								
	Key Data Points				13	14	15	16	
TOTAL (Gross Weight) (kg.)		34 666	14 745	49 411	120 070	490 688	2281983	2942152	
Design Envelope Volume (m^3)				260.57	765.12	1976.52	2888.32	5890.53	
Pressurized Volume (m^3)				17.44					
Design Envel Surf Area (m^2)				283.73	[b]427.73	[b]784.10	[b]1147.35	2688.15	
Pressurized Surf Area (m^2)									
Design q, Max (kg/m^2)									
Design g, Max									
Design Power, Max (KW)									
Design No. Men Days				3/10					

DESIGNATIONS:

Code, System; Ref. MIL-M-38310A or SP-6004

Item or Module

- A Apollo Spacecraft (fig. A-3(a))
- B Lunar Module (fig. A-4(a))
- C A+B (Launch Payload)
- D S-IVB Stage and Instrument Unit 13
- E S-II Stage 14
- F S-IC Stage 15

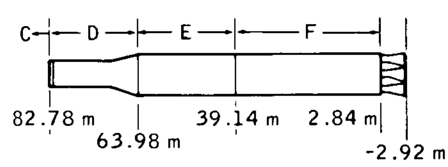
Spacecraft

- M Manned Launch C+D+E+F 16
- U Unmanned Launch

NOTES & SKETCHES:

[a]G.F.E. is government-furnished equipment.

[b]Sidewall only.



(a) International System of Units (SI Units).

Figure A-5. - Spacecraft Summary Weight Statement for Apollo spacecraft and Saturn V booster.

SPACECRAFT SUMMARY WEIGHT STATEMENT

CONFIGURATION	BY	DATE
Saturn V-Apollo	Mass Properties Section	August 1966

CODE	SYSTEM	ITEM OR MODULE A	B	C	D	E	F	SPACECRAFT M	U
1.0	Aerodynamic Surfaces	323		323			2 054	2 377	
2.0	Body Structure	8 827	2 020	10 847	13 686	62 169	140 108	226 810	
3.0	Induced Envir Prot	5 504	670	6 174				6 174	
4.0	Lnch Recov & Dkg	965	530	1 495				1 495	
5.0	Main Propulsion	4 382	1 582	5 964	6 171	26 142	139 510	177 787	
6.0	Orient Control Sep & Ull	1 357	357	1 714	1 747	2 280	639	6 380	
7.0	Prime Power Source	1 600	942	2 542	2 157	871	947	8 740	
8.0	Power Conv & Distr	1 692	531	2 223					
9.0	Guidance & Navigation	595	121	716	645		57	1 418	
10.0	Instrumentation	116	135	251	1 877	4 432	3 400	9 960	
11.0	Communication	449	124	573				573	
12.0	Environmental Control	773	388	1 161	952	1 198	334	3 645	
13.0	(Reserved) G.F.E.[a]		941	941				941	
14.0	Personnel Provisions	422	151	573				573	
15.0	Crew Sta Contrl & Pan	396	242	638				638	
16.0	Range Safety & Abort				72	283	402	757	
SUBTOTALS (Dry Weight)		27 401	8 734	36 135	27 307	97 375	287 451	448 268	
17.0	Personnel	1 075		1 075				1 075	
18.0	Cargo								
19.0	Ordnance	571	52	623	116	835	2 425	3 999	
20.0	Ballast	958		958				958	
21.0	Resid Prop & Serv Items	1 167	390	1 557	898	5 194	31 704	39 353	
SUBTOTALS (Inert Weight)		31 172	9 176	40 348	28 321	103 404	321 580	493 653	
22.0	Res Prop & Serv Items				943	1 805	21 401	24 149	
23.0	Inflight Losses	2 333	1 019	3 352	4 477	3 765		11 594	
24.0	Thrust Decay Propellant				188	400	1 770	2 358	
25.0	Full Thrust Propellant	42 919	22 313	65 232	230 050	970 001	4598260	5863543	
26.0	Thrust Prop Buildup				730	2 406	87 900	91 036	
27.0	Pre-Ignition Losses								
	Actual Weight Adjustment								
	Key Data Points				13	14	15	16	
TOTAL (Gross Weight) (Lb)		76 424	32 508	108 932	264 709	1081781	5030911	6486333	
Design Envelope Volume (Ft^3)				9 202	27 020	69 800	102 000	208 022	
Pressurized Volume (Ft^3)				616					
Design Envel Surf Area (Ft^2)				3 054	[b]4 604	[b]8 440	[b]12 350	28 935	
Pressurized Surf Area (Ft^2)									
Design q, Max (Lb/Ft^2)									
Design g, Max									
Design Power, Max (KW)									
Design No. Men/Days				3/10					

DESIGNATIONS:

Code, System; Ref. MIL-M-38310A or SP-6004

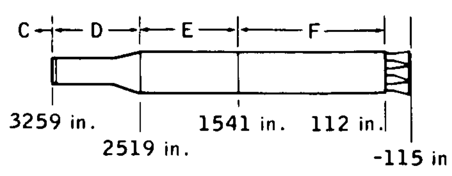
Item or Module
- A Apollo Spacecraft (fig. A-3(b))
- B Lunar Module (fig. A-4(b))
- C A+B (Launch Payload)
- D S-IVB Stage and Instrument Unit 13
- E S-II Stage 14
- F S-IC Stage 15

Spacecraft
- M Manned Launch C+D+E+F 16
- U Unmanned Launch

NOTES & SKETCHES:

[a]G.F.E. is government-furnished equipment.

[b]Sidewall only.



(b) Customary U. S. Units.

Figure A-5. - Concluded.

SPACECRAFT SUMMARY WEIGHT STATEMENT									
CONFIGURATION Aircraft (typical samples)			BY Mass Properties Section			DATE			
CODE	SYSTEM	ITEM OR MODULE						SPACECRAFT	
		A	B	C	D	E	F	M	U
1.0	Aerodynamic Surfaces	1 619	4 672	6 038	19 685	18 256	44 502		
2.0	Body Structure	1 508	5 225	3 232	12 125	13 309	49 617		
3.0	Induced Envir Prot								
4.0	Lnch Recov & Dkg	406	1 178	1 792	6 093	4 959	17 185		
5.0	Main Propulsion	2 763	5 446	9 671	19 273	13 781	19 919		
6.0	Orient Control Sep & Ull	590	991	821	1 976	2 300	4 825		
7.0	Prime Power Source	145	419	655	2 743	1 449	2 149		
8.0	Power Conv & Distr								
9.0	Guidance & Navigation [a]	242	1 251	1 740	3 609	1 293	1 977		
10.0	Instrumentation [b]	86	151	207	431	521	470		
11.0	Communication								
12.0	Environmental Control	85	289	450	304	1 150	1 736		
13.0	(Reserved) [c]	31	293	426	1 974				
14.0	Personnel Provisions	71	445	399	962	2 267	3 268		
15.0	Crew Sta Contrl & Pan	7	33	20	68	60	46		
16.0	Range Safety & Abort								
SUBTOTALS (Dry Weight)		7 553	20 393	25 451	69 243	59 345	145 694		
17.0	Personnel	122	242	330	792	912	740		
18.0	Cargo	1 077	7 319	3 273	9 245	14 061	57 250		
19.0	Ordnance								
20.0	Ballast								
21.0	Resid Prop & Serv Items	43	209	464	868	602	659		
SUBTOTALS (Inert Weight)		8 795	28 163	29 518	80 148	74 920	204 343		
22.0	Res Prop & Serv Items								
23.0	Inflight Losses								
24.0	Thrust Decay Propellant								
25.0	Full Thrust Propellant	3 742	14 579	44 418	141 205	69 322	144 469		
26.0	Thrust Prop Buildup								
27.0	Pre-Ignition Losses								
	Actual Weight Adjustment								
	Key Data Points	17	18	19	20	21	22		
TOTAL (Gross Weight) kg W_{TO} [d]		12 537	42 742	73 936	221 353	144 242	348 812		
Design Envelope Volume (m^3)		30.98	76.26	120.91	647.46	652.14	3066.01		
Pressurized Volume (m^3)		1.56	3.23	9.88	51.82	387.94	1858.49		
Design Envel Surf Area (m^2)		166.85	286.33	581.39	1526.21	1275.47	3162.23		
Pressurized Surf Area (m^2)									
Design q, Max (kg/m^2)									
Design g, Max [e]		9.6	11.0	3.0	2.7	3.75	3.75		
Design Power, Max (KW)									
Design No. Men/Days		1/	2/	3/	6/	8/	6/		

DESIGNATIONS:

Code, System; Ref. MIL-M-38310A or SP-6004

Item or Module

A	F8U-1	July 1959	17
B	F-111A	October 1967	18
C	B-58A	October 1957	19
D	B-52G	July 1959	20
E	C-141A	May 1967	21
F	C-5A	February 1967	22

Spacecraft

M Manned Launch

U Unmanned Launch

NOTES & SKETCHES:

[a] Electronics group (ref. 3).

[b] Instruments and navigational equipment group and photographic group (ref. 3).

[c] Miscellaneous unassigned.

[d] Maximum take-off weight.

[e] Ultimate flight-stress gross weight varies between 0.74 W_{TO} to W_{TO}.

(a) International System of Units (SI Units).

Figure A-6. - Spacecraft Summary Weight Statement for various aircraft.

SPACECRAFT SUMMARY WEIGHT STATEMENT

CONFIGURATION	BY	DATE
Aircraft (typical samples)	Mass Properties Section	

CODE	SYSTEM	ITEM OR MODULE A	B	C	D	E	F	SPACECRAFT M	U
1.0	Aerodynamic Surfaces	3 569	10 301	13 312	43 399	40 247	98 111		
2.0	Body Structure	3 324	11 520	7 126	26 731	29 342	109 387		
3.0	Induced Envir Prot								
4.0	Lnch Recov & Dkg	896	2 597	3 951	13 432	10 934	37 887		
5.0	Main Propulsion	6 091	12 006	21 322	42 490	30 381	43 914		
6.0	Orient Control Sep & Ull	1 301	2 184	1 809	4 357	5 070	10 636		
7.0	Prime Power Source	319	924	1 443	6 047	3 195	4 738		
8.0	Power Conv & Distr								
9.0	Guidance & Navigation a	533	2 758	3 835	7 957	2 850	4 358		
10.0	Instrumentation b	190	333	456	950	1 148	1 036		
11.0	Communication								
12.0	Environmental Control	187	637	993	670	2 535	3 828		
13.0	(Reserved) c	68	646	939	4 353				
14.0	Personnel Provisions	158	980	880	2 120	4 998	7 204		
15.0	Crew Sta Contrl & Pan	15	73	45	149	133	102		
16.0	Range Safety & Abort								
SUBTOTALS (Dry Weight)		16 651	44 959	56 111	152 655	130 833	321 201		
17.0	Personnel	270	533	727	1 747	2 011	1 631		
18.0	Cargo	2 375	16 136	7 216	20 382	31 000	126 214		
19.0	Ordnance								
20.0	Ballast								
21.0	Resid Prop & Serv Items	94	460	1 022	1 913	1 327	1 454		
SUBTOTALS (Inert Weight)		19 390	62 088	65 076	176 697	165 171	450 500		
22.0	Res Prop & Serv Items								
23.0	Inflight Losses								
24.0	Thrust Decay Propellant								
25.0	Full Thrust Propellant	8 250	32 142	97 924	311 303	152 829	318 500		
26.0	Thrust Prop Buildup								
27.0	Pre-Ignition Losses								
	Actual Weight Adjustment								
	Key Data Points	17	18	19	20	21	22		
TOTAL (Gross Weight) (Lb) W_{TO} [d]		27 640	94 230	163 000	488 000	318 000	769 000		
Design Envelope Volume (Ft^3)		1 094	2 693	4 270	22 865	23 030	108 275		
Pressurized Volume (Ft^3)		55	114	349	1 830	13 700	65 632		
Design Envel Surf Area (Ft^2)		1 796	3 082	6 258	16 428	13 729	34 038		
Pressurized Surf Area (Ft^2)									
Design q, Max (Lb/Ft^2)									
Design g, Max [e]		9.6	11.0	3.0	2.7	3.75	3.75		
Design Power, Max (KW)									
Design No. Men/Days		1/	2/	3/	6/	8/	6/		

DESIGNATIONS:

Code, System; Ref. MIL-M-38310A or SP-6004

Item or Module

A	F8U-1	July 1959	17
B	F-111A	October 1967	18
C	B-58A	October 1957	19
D	B-52G	July 1959	20
E	C-141A	May 1967	21
F	C-5A	February 1967	22

Spacecraft

M Manned Launch

U Unmanned Launch

NOTES & SKETCHES:

[a] Electronics group (ref. 3).

[b] Instruments and navigational equipment group and photographic group (ref. 3).

[c] Miscellaneous unassigned.

[d] Maximum take-off weight.

[e] Ultimate flight-stress gross weight varies between 0.74 W_{TO} to W_{TO}.

(b) Customary U.S. Units.

Figure A-6. - Concluded.

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